At the time of issue this report has not been published. Any author desiring to quote this paper should refer to it as "A paper of the Meteorological Research Committee (London), M.R.P. No.875 by Dr. D.G. James. A copy is available in the Library of the Meteorological Office."

M.R.P. 875

S.C.III/172

31st August, 1954

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

Fine scale characteristics of the lowest 5,000 ft of the atmosphere as observed from an aircraft

by

D.G. James (Meteorological Office)

Summary

Data derived from observations made by an aircraft of the Meteorological Research Flight of small scale disturbances in the lowest 5,000 ft of the atmosphere are discussed. Flights were made over land and sea at times when thermal convection was thought to be active over land.

Sensitive instruments were used to measure gustiness and fluctuations of temperature and dew point from 500 ft to 5,000 ft above ground, and the records obtained are compared with some theories on thermal convection. A tentative suggestion is offered to explain some of the phenomena recorded.

A short statistical summary of several of the flights is given together with some examples of the camera records obtained from the sensitive instruments.

1. Introduction

Twenty three flights were made by a Hastings aircraft of the Meteorological Research Flight between June 1952 and August 1953 at times when thermal convection was expected to be active over land. Six of these flights were carried out over the sea, when the vertical temperature profile of the air mass had been modified by transport over a cold surface. Preliminary analysis of early flight data indicated modifications necessary to the flying technique of subsequent flights in order to obtain the maximum of desirable information.

A short statistical summary of the results obtained from the flights is given, but although the histograms presented serve to illustrate the broader features of thermal convection over land, it must be emphasised that the parameters vary considerably from flight to flight.

Any investigation of thermal convection over a land area must necessarily include the effects of forced convection due to surface friction. Precautions taken to minimise these effects were (i) flights were made on calm or near calm days with approximately the same surface wind direction (ii) on each occasion the flights were made over the same area.

Table I shows the number, date and time of each flight, the instruments used and the flight procedure adopted.

2. Instruments

(a) Ultra rapid thermometer

To measure small fast fluctuations of temperature, a speedy sensitive thermometer was used the lag of which was some 5 msec. (Grant, 1950). This instrument was situated below the nose of the aircraft when in use, but could be withdrawn into a wooden fairing for protection on the ground and in cloud.

/(b)

(b) Hot wire anemometers

The gustiness of the airstream was detected and measured by two sensitive hot wire anemometers (Murgatroyd and James, 1953), the display and recording system being that of the ultra rapid thermometer. One of these anemometers, situated below the nose of the aircraft, was non-directional and measured the total airspeed fluctuations, including those of the aircraft itself.

The second anemometer, mounted 5 to 6 ft forward of the nose, was unidirectional and measured upgusts and downgusts only, the output being independent of aircraft speed.

(c) Automatic frost point hygrometer

Towards the end of the sequence of flights, an automatic hygrometer became available for use. This instrument, constructed by Dr. A.W. Brewer of the Clarendon Laboratory at Oxford, was readily adaptable to the display system of the ultra rapid thermometer and consequently continuous records of dew points could be obtained. The hygrometer has shown in extensive tests, that it followed fluctuations in dew and frost points rapidly and faithfully, the lag of the thermometer element being less than 1 sec and its accuracy better than 1.0°F at dew points around 40°F.

(d) Dobson-Brewer frost point hygrometer

The mean value of the frost or dew point was obtained in level flight by the use of a manual frost point hygrometer. This instrument was slow, a frost point being obtained every 10 sec in level flight and its accuracy was of the order of $\pm$ 1°F.

(e) Meteorological Office flat plate thermometer

Mean absolute values of temperature were obtained by use of a standard flat plate thermometer. This instrument was slow, its lag being of the order of 8 sec, but it provided an average value for any given level run, the usual corrections being applied for height and airspeed.

(f) Altimeter and airspeed indicator

Height and airspeed were recorded from standard aircraft instruments, accurate to within $\pm$ 10 ft and $\pm$ 1 kt respectively when flying straight and level below 6,000 ft. These instruments had lags of about 2 - 3 sec. For runs below 500 ft over the sea, the radio altimeter was frequently used.

(g) Accelerometer

The response of the aircraft to any turbulence encountered was recorded by a standard accelerometer. This instrument had a full scale deflection of $\pm$ 0.25 g, records being obtained on positive photographic film.

3. Operational procedure

On a convection flight a crew of six was usually taken, consisting of pilot, engineer, and four observers. Visual observations of height, airspeed, temperature as given by the Meteorological Office flat plate thermometer, dew point, amount and type of the cloud above, and nature of the ground below were made every 10 sec. Continuous time-marked records were obtained of each sensitive instrument in turn.

To reduce the effect of any forced convection, and any variation in thermal convection brought about by a change of ground surface, all flights over land were flown along a line joining two well defined land positions some seven miles apart. Over the sea, such definition was not necessary, provided that the air had a long sea track before reaching the area to be investigated. However, all runs over the sea were performed in a north-south direction over the English Channel, the northernmost point being some two miles south of Brighton.

/Two

Two types of flights were performed. At first, readings were confined to those made in level flight. On these flights several runs were made at 500 ft intervals from 500 ft above ground up to cloud base, the altimeter having been set to read directly heights above the average ground level over which the flight was executed. Although constant height, airspeed and attitude were desirable, preference was given to constant height when fluctuations of temperature were being recorded, constant airspeed for the measurement of omnidirectional gustiness, and constant attitude for the measurement of upgusts and downgusts. The mean airspeed always required was 120 kt and it is to the credit of the pilots that little variation on this figure was obtained even in the most turbulent conditions, and that the sensitive instruments rarely suffered any damage due to excessive speed. Each run at a given height usually lasted three minutes, during which the film records of the sensitive instruments were marked every minute. Calibration of the ultra rapid thermometer was carried out at the end of each run.

Towards the end of the series of flights, slow descents were performed at constant airspeed, direction and rate of descent. As before, continuous records of the sensitive instruments were obtained from 6-7,000 ft down to 500 ft, with spot readings of temperature, height, airspeed and frost point every 250 ft of height.

No special effort was made to fly at particular times of day, the flights being almost evenly divided between morning and afternoon, with one flight at night.

4. Data from flights over land

Table 2 presents data obtained from level runs on eleven flights when the ultra rapid thermometer, hot wire anemometers, and accelerometer were used. Mean values of temperature, obtained by the flat plate thermometer, at each level are given, together with the mean frost point obtained from the manual hygrometer. The mean temperature given at 1,000 ft on 31 March 1953 in Table 2 is suspect. A reading error of 5°F would give 40.6°F as the temperature at this level, though such errors are uncommon with the Meteorological Office flat plate thermometer. The average maximum variation from mean values is given under the heading of 'Span'.

Data from records of descents over land are presented in Tables 6, 7, 8, 9, 11, 14 and 15. The flights were undertaken to determine the structure of the vertical temperature distribution on convective days.

(a) Temperature

Level runs were carried out at 500 ft and at intervals up to cloud base, and occasionally above this level. From close study of the observations made on these runs, it seems that the region from ground to cloud base can be divided into three layers.

Figs. 4 and 5 are histograms of frequency per minute flying time (i.e. 12,000 ft) of the temperature excess and horizontal extent of temperature pulses recorded in level flight through these three layers.

(i) The first layer extending from ground to 800 or 1,200 ft, depending on the time of day, the cloud cover and the surface wind strength, seems to be a region of chaotic temperature fluctuations (Fig.9). The number of fluctuations in this layer is extremely large, some fifteen or twenty being encountered in a horizontal run of some 40,000 ft whilst the temperature excess varies from 0.2°F to 1.8°F (Fig. 4) though isolated examples have been observed when the temperature excess was 4.0°F. The upper surface of this layer, though well marked, is by no means flat; straight and level flight at this height results in this boundary being crossed and recrossed several times.

/The

The lapse rate in this layer is frequently super adiabatic, though the number of temperature fluctuations encountered renders an accurate estimation extremely difficult.

(ii) A second layer apparently extends from the top of this turbulent layer to some 200 to 300 ft below cloud base, this latter value being a function of the time of day, and of the vertical temperature profile of the ambient air (Fig. 10). The layer is characterised by positive temperature pulses which show a definite preference for an excess of 0.2 to 0.3°F though a preferred horizontal dimension is less apparent (Figs. 4 and 5). The average horizontal extent is 500 to 700 ft though occasional pulses have been measured with 1,500 ft diameter (Fig. 5). The slow variation in temperature of the ambient air, possibly produced by the passage through it of the warm pulses, is considerably less than in the lower turbulent layer, but increases somewhat with height. No evidence is found to indicate that the temperature pulses increase in diameter with height, the spectrum of pulse sizes being similar for all levels in this intermediate layer. It is noticeable that for two consecutive runs at the same height in this region, there is a considerable variation in the number of pulses encountered.

The lapse rate in this layer is approximately dry adiabatic, though on all descents small layers of more stable air are observed. These sub-layers, characterised by an isothermal or small temperature inversion of the order of 0.5°F are usually 100 to 200 ft thick, but are not permanent configurations of the vertical temperature profile of the air mass. Consecutive and similar descents do not indicate the presence of these more stable layers at the same heights, though on average their frequency of occurrence - some two or three per descent - remains fairly constant.

(iii) The third layer extending from cloud base down to some 200 to 400 ft below, called the "sub-cloud layer" by other authors, is characterised by an increase in stability of the vertical temperature gradient (Fig. 12). Frequently, this layer is composed of several shallow strata in which the vertical temperature gradient is either zero or slightly positive. The layer varies in depth during the day and seems to become more prominent during the afternoon. If the cloud base lifts during the day, the sub-cloud layer extends upwards and becomes more stable. If the cloud disappears, the height of the original cloud base becomes a preferred height for the formation of a more stable layer. In all cases, however, random temporary isothermals and inversions are recorded at all levels from the top of the turbulent layer to the maximum height reached during any flight.

Fig. 8 indicates the percentage of horizontal runs, (3 min at 120 kt) where the total temperature variation recorded exceeds a given value. It can be clearly seen from this figure that the amplitudes of the long-wave temperature fluctuations are quite small in the intermediate layer, but are large both in the turbulent layer and in the sub-cloud layer. At the lower levels of the sub-cloud layer, the number of warm pulses encountered decreases, but increases again just below cloud base. A feature of this layer is the presence of long-wave temperature fluctuations recorded on a level run (Fig. 11), the amplitude being of the order of 2°F near cloud base, with wavelength varying from 3,000 to 8,000 ft. Some positive temperature fluctuations are also recorded in this layer, with magnitudes of the order of 0.2°F, and horizontal extents of less than 100 ft.

(b) Gustiness, as recorded by the hot wire anemometers

The three layers described above are again evident from observations of gustiness, particularly in the records of the directional hot wire anemometer.

Figs. 6 and 7 are histograms of frequency per minute flying time (i.e. 12,000 ft) of the magnitudes and horizontal extents of gusts recorded in level flights through these three layers.

/(i)

(i) In the lower turbulent layer continuous gustiness is experienced by both anemometers (Fig. 9). The results show that the gusts are well defined, with sharp edges and occasional flat tops. Their magnitudes are in general up to 10 to 12 ft/sec, though a few of 15 to 20 ft/sec have been recorded (Fig. 6). The horizontal extents of the gusts vary from 200 to 1,500 ft, their frequencies and extents being given by Fig. 7.

A characteristic of this layer is that the number of upgusts recorded is only slightly greater than the number of downgusts. The upper boundary of the turbulent layer is clearly seen on the records of descents using the directional hot wire anemometer, being marked by a sudden increase in the number of gusts recorded.

(ii) In the intermediate layer the gusts are less frequent, more isolated, and in this respect better defined than those in the lower layer. The gust size is in general some 4 to 6 ft/sec at all heights in this region, though a few have been recorded of up to 15 ft/sec (Fig. 6). The horizontal extent of a gust in this layer is variable, the average value being 500 to 600 ft (Fig. 7). A feature of this layer is the difference in background noise in the records of the two anemometers. The directional anemometer gives a well-defined trace, with occasional well-defined and isolated upward gusts. This possibly indicates that nearly all the vertical motion in this layer is due to the upward transport of air by warm temperature pulses. The non-directional anemometer, however, has considerable background noise which extends throughout the record, and which indicates either the presence of horizontal vector gustiness in this layer, or uneveness of aircraft performance.

(iii) The third layer, near cloud base, is characterised by a decrease in frequency of the isolated gusts (Fig. 11) and in the background noise of both anemometers. The gusts recorded are in general similar to those at lower levels, the average being 5 to 8 ft/sec (Fig. 6) and are accompanied by slower long-wave changes in airspeed, usually obtained on the trace of the non-directional anemometer. This fluctuation has neither constant amplitude nor constant wave length, amplitudes of 3 to 8 ft/sec and wavelengths of 3,000 to 8,000 ft being observed. Sudden downgusts of magnitudes up to 5 ft/sec are evident in this layer on the directional anemometer trace, though the frequency of occurrence is small.

(c) Bumpiness, as recorded by an accelerometer

The boundary between the lower and middle layers is extremely well marked on the accelerometer trace, though the corresponding division between the middle and upper layers is not obvious.

(i) In the lower layer the bumps recorded are very frequent (Figs. 1 and 9) the accelerometer trace being one of continuous bumps which show a preference for sizes between 0.10g and 0.15g, though the largest recorded is greater than 0.3g. The horizontal extent of these bumps varies from 300 ft to 700 ft, the average extent being about 500 ft.

(ii) The middle layer indicates a marked decrease in the number of bumps encountered over a given time (Fig. 1) and the presence of long "quiet" periods, sometimes as great as 6,000 ft when no bumps greater than 0.10g are recorded (Fig. 10). The average size of a bump in this layer shows little variation, being 0.13g to 0.16g at the lower and 0.14g to 0.17g at the higher levels. There is a steady decrease with height in the number of bumps encountered in this region, though the average horizontal extent shows little change from 500 to 600 ft.

(iii) The records obtained in the third layer near cloud base indicate a slight increase in the frequency of occurrence of bumps, whilst there is a marked decrease in the size and number of "quiet" periods. Otherwise the average size and horizontal extent of a bump in this layer differs little from those of a bump in the middle region.

/In

In the presence of a temperature inversion, the size and frequency of bumps recorded varies considerably as the aircraft descends through the stable layer, reaching a maximum at the base of the layer.

(iv) Above cloud, the bumps recorded show not only a sharp decrease in frequency and intensity, but also differ in shape, from those at lower levels. Whereas at lower levels the bumps are generally well-defined with steep sides, above cloud they appear more as undulations.

5. Data from flights over the sea

Data are presented in Table 3 from two flights over the sea when records were obtained of temperature fluctuations, gustiness and bumpiness. In Tables 10, 12, 13 and 16, data from the records of slow descents over the sea are given. Although in four of the six flights described no convective type cloud was evident over the sea, thermal convection was active over the land. These results are presented so that a comparison may be made between phenomena observed at similar heights over land and sea. A short discussion is now given of the observations made on these flights.

(a) Temperature

There is no evidence for the formation of three well-defined layers at heights similar to those over land.

Slow descents from 6,000 ft to 100 ft above the sea frequently show the presence of a well-defined inversion at the lower levels (Fig. 16). Consecutive descents in the same area indicate a considerable change in the height and thickness of this layer, which becomes more pronounced as several hours elapse between descents (Tables 12 and 13). This inversion serves as a dividing line between two very different states of disturbance.

Below the inversion, numerous positive pulses of temperature excess are recorded, having magnitudes up to 0.8°F with horizontal extents to 600 ft in a lapse rate which is nearly isothermal (Fig. 14). Long-wave negative pulses of temperature excess are also recorded in level flight at these heights, and may be accounted for by variations in the inversion.

Above the inversion, positive pulses of temperature excess are recorded which are similar to those in the intermediate layer over land, though fewer in number (Fig. 15). The lapse rate in this region is disturbed by the presence of shallow layers of more stable air, again similar to those over land (Fig.16).

(b) Gustiness

In general, gustiness observed over the sea is small, individual gusts being mainly 2 - 3 ft/sec with occasionally a larger gust of 5 to 6 ft/sec. The frequency of occurrence of gusts falls off considerably with height, few being found above 1,500 ft.

(c) Bumpiness

In general, the majority of bumps experienced by the aircraft between 6,000 ft and 250 ft above sea level are less than 0.10g. A few individual bumps, however, are as large as 0.17g and are in association with pulses of warm air recorded by the ultra rapid thermometer.

The greatest proportion of bumps encountered occurs below 500 ft (Fig.2). The trace at this level exhibits continuous bumpiness, with a maximum on one flight of 0.15g. The frequency of the bumps falls off rapidly until at 2,000 ft few of measurable size are found.

The bumps over sea have a different character from those experienced over land, resembling smooth undulations as opposed to sharp edged pulses. Extensive regions are found on the descent where no bumps at all are recorded, extending as deep as 500 ft in the vertical, and some 12,000 ft in the horizontal.

/6.

6. Data from flights with the automatic hygrometer

Observations made on flights with the automatic hygrometer are presented in Table 4, for two flights over land and one over sea. The ultra rapid thermometer and accelerometer were usually employed on the same flight, and some comparison can be made of the excess of temperature and dew point of a thermal pulse.

Considering first the two flights, numbers 21 and 22, on 28 July 1953 over land, all levels indicate the presence of wet and dry patches, with variations of dew point of 4 - 6°F from that of the ambient air. The morning flight shows well defined pulses of the same order of dew point excess up to 1,500 ft, but at this level and up to cloud base the variations in dew point are slow. At the lower levels, the temperature pulses have an excess of up to 1.3°F at 500 ft and 0.6°F at 1,000 ft, whilst long-wave changes of 0.4 - 0.7°F amplitude are recorded at 1,500 ft and 2,000 ft with few faster fluctuations. The records of the afternoon flight indicate a warming of the air from 500 ft to 2,000 ft of some 3 - 4°F, with no significant change in mean dew points. Temperature fluctuations take the form of fast positive pulses of 0.2 - 0.4°F excess, with a slow change of 1.0°F appearing at 2,500 ft. Towards the end of the temperature traces obtained at the lower levels, there is a sharp well-defined drop of temperature, being 1.3°F at 500 ft, 1.0°F at 1,000 ft and 0.5°F at 1,500 ft, at which height the full horizontal extent of this cold patch was 5,000 ft. This change in temperature is accompanied at 500 ft by a sudden increase in dew point of 4°F - the runs are made on reciprocal headings, and the end of the patch appears as a sudden decrease in dew point - but there is little evidence of this cold wet patch on the hygrometer trace at higher levels. In general, the rapid changes of dew points recorded are some 2 - 4°F in excess of that of the ambient air, at levels up to 2,000 ft, with long-wave changes of 6°F appearing from 1,000 ft to 2,000 ft. Above this level, fluctuations of dew point occur as well marked groups of pulses with an excess of 1 - 2°F.

Flight 23, over the sea, shows very many temperature fluctuations of 0.5°F at 100 ft decreasing in number and size up to 3,000 ft. At this level and at 1,000 ft long-wave changes of 0.5°F are evident, those at the higher level having a half wavelength of 6,000 ft. The automatic hygrometer records show well-defined pulses of wet air at 100 ft and 500 ft with an excess dew point of 2 - 3°F. At 1,000 ft eight well-defined pulses are recorded of 4 - 5°F excess dew point. These are very evenly spaced, there being some 4,500 - 5,000 ft horizontal distance between them. A slow descent made on completion of the level runs (Table 16) indicates an inversion of 1.0°F between 800 ft and 900 ft, and it seems probable that the upward transport of water vapour is being limited by the inversion. Above 1,000 ft few pulses of moist air are observed, only three being evident at 2,000 ft of 2°F excess dew point. At 3,000 ft no well-defined pulses are recorded the only variation in dew point being a long-wave change of 5°F.

7. Statistical analysis of accelerometer traces

A complete statistical analysis has not been made of all the accelerometer traces obtained on these convection flights. However, the bumps greater than 0.1g obtained on some 20 level flights have been counted, and are presented in a form of histograms, for land and sea (Figs. 1 and 2). In these diagrams the total number of bumps per minute flying time (i.e. some 12,000 ft) is plotted against height. On the average, about ten runs are made at each level from 500 to 3,000 ft over land, and three runs over the sea. Cases are only considered when the cloud base was about 3,000 ft or above, or alternatively when there was no low cloud. It can be seen at once from Fig. 1 that there is a sharp decrease from 5.7 to 3.5 bumps/min between 1,000 ft and 1,500 ft with further smaller drops up to 2,500 ft. At 3,000 ft, in general near cloud base, the number of bumps per minute increases slightly. Over the sea, there is a continuous falling off with height, though in all cases the number of bumps recorded is considerably less than over land.

/On

On six flights, numbers 3 to 8, each bump recorded has been tabulated according to its magnitude, horizontal duration, and mean value. The mean value is defined as that value, which when multiplied by the horizontal extent of the bump, gives the area enclosed between the accelerometer trace and the line of no acceleration. Table 5 shows the mean value of such characteristics of the accelerometer traces for occasions when cloud base was 3,000 ft or above. The first column shows the number of bumps greater than 0.10g at heights from 500 ft to 2,500 ft. A sharp decrease can be found between 1,000 ft and 1,500 ft when the total number of bumps per minute flying time falls from 6.2 to 4.6. The second, third and fourth columns of the table show respectively the average maximum, average duration, and average mean of all bumps at each height. The fifth column shows the average area enclosed for each bump, between the accelerometer trace and the line of no acceleration. Bunker (1952) obtained a number of accelerometer traces in a series of similar flights over sea, and defined a "Turbulence Index" for any height as the average area enclosed between the accelerometer trace and the line of no acceleration over ten seconds at that height. The sixth column shows the average turbulence index for each height from 500 ft to 2,500 ft for the six flights analysed.

8. Notes on the comparison of our observations with previous ideas on convection proposed by other authors

(a) Bunker (1953) shows, by an extension of the equations of Houghton and Cramer, how under certain conditions a thermal bubble can pass through a turbulent layer and still maintain its identity. He shows a diagram of the temperature profile of such a bubble at 350 ft moving upwards at about 8 ft/sec with a temperature excess of about 1.3°F. This agrees well with our temperature observations at 500 ft, which show similar temperature pulses moving at 6 - 8 ft/sec with a temperature difference of 0.5 - 1.5°F. However, it is difficult to conceive of a turbulent region obeying his conditions at all points independent of time. Indeed this is not the case since the frequency of occurrence of pulses falls off very rapidly above 1,000 ft.

Bunker also concludes that bubbles of some 250 ft horizontal extent have a temperature excess of 0.5°F and a vertical velocity of 2 ft/sec whilst those of 1,500 ft horizontal extent have a temperature excess of about 1.0°F and a vertical velocity of 3 to 5 ft/sec. This does not agree with our observations at 500 ft which indicate little variation of temperature excess with horizontal extent.

(b) Bunker (1952) presents a diagram showing the divisions into which the first 3,000 ft or so of the atmosphere have been divided by various authors. Some of these authors suggest the three layers which are indicated by the measurements made by the Meteorological Research Flight. Fig. 3 shows a typical division made in the light of our observations, assuming a cloud base of 3,000 ft.

Bunker (1952, page 9) states that an inversion is capable of severely limiting the transport of water vapour, which agrees entirely with our observations over sea. It has been shown that positive pulses of temperature have been observed above an inversion over the sea on flights 11 and 12, whilst there was no cumulus forming. A later flight, number 23, confirmed that there was a sharp drop in dew point above the top of the inversion, although numerous wet pulses were observed in the inversion itself. It seems therefore that the warm pulses observed in flights 11 and 12 came from the top of the inversion, and hence contained much drier air than any bubble rising directly from the sea.

Bunker also comments upon "the process of destroying the original inversion and of forming a new inversion at a higher or a lower level." This agrees well with the observations between the top of the turbulent layer and cloud base, where several small inversions can be observed.

/(c)

(c) Langwell (1953) suggests that an inversion 2,000 ft above the sea oscillates about this height and can, under certain circumstances, form small cumulus clouds at the peaks. No fixed inversion has been found by the Meteorological Research Flight at the height Langwell suggests. However, on three flights, numbers 19, 20a and 23, an inversion has been observed below 1,000 ft. Above the top of the inversion a few positive pulses of temperature have been observed, whilst below the inversion these pulses are considerably more frequent. On consecutive descents, considerable variation in the thickness of the inversion has been recorded (flight 20a), which could be attributed to long-wave oscillations in the layer.

(d) In a comprehensive article on convection, Ludlam and Scorer (1953) quote Hohnsdorft as suggesting that the presence of a hill or good thermal source would send up a shower of bubbles followed by a long pause, when the cold air replacing the warm ascending air would itself warm up. This fits our observations well, since, for two successive level runs at a given height outside the friction layer, considerable variation is obtained in the number of warm pulses found for a given time.

Ludlam & Scorer (1953) suggest that below a convection bubble there is a wake which consists of a mixture of the warm air of the bubble with the surrounding air through which it has passed. It is clear that rapid temperature fluctuations as recorded by the ultra rapid thermometer can be divided into two groups, namely those consisting of well-defined sharp edged pulses, and those which seem to be small bursts of temperature. These latter are usually smaller in excess temperature than any isolated pulse at the same height, and also have greater horizontal extent. It is possible that these small bursts of fluctuation are part of the wake of a bubble, though the evidence is not sufficient to be conclusive.

It is also claimed that the horizontal extent of thermal bubbles increases with height, but this is not supported by either the temperature records or those of the accelerometer.

9. Discussion

From the above accumulation of data, it seems evident that the atmosphere from ground to cloud base may be divided into three layers, each having its own characteristics. A short discussion follows of the observations made in these regions.

(a) The turbulent ground layer

The first division may be made at a height above which the numbers of temperature pulses and their temperature excesses are considerably less than are the corresponding quantities below it. This boundary is recorded as being always above 500 ft and always below 1,500 ft though the 1,000 ft level is sometimes below and sometimes above this line. In all probability the height of the line varies from 800 ft to 1,200 ft, the exact height depending on the surface wind and the vigour of thermal convection on any particular day.

The exact method of formation of a temperature pulse on the ground is still open to conjecture, but may take the following form. A volume of air is warmed by being in contact with the ground, which for some reason, probably the constitution of the surface, is subject to some form of differential heating (Bleeker and Andre 1950). The break away of the bubble is possibly caused by the surface wind and by thermal instability and seems to take place at irregular intervals. At 500 ft a typical temperature pulse would have a measured temperature excess of 1.0 to 1.5°F, a horizontal extent of 400 to 600 ft, an excess dew point of 5 to 7°F, and would be moving at 6 to 8 ft/sec relative to the air though this velocity is not entirely vertical. These pulses are extremely numerous, with very sharp and well-defined edges, existing in a lapse rate which is frequently super-adiabatic.

/(b)

(b) The intermediate layer

Above the boundary proposed in (a) above, but below a line drawn some 200 to 400 ft below cloud base, there exists a region which we have referred to as the intermediate layer. Its lower boundary is determined by a decrease in the frequency of occurrence of temperature pulses and a sudden change in the temperature excess of such a bubble. The upper boundary is determined chiefly by the sudden occurrence of a more stable layer just below cloud. At any point within this intermediate layer, a typical pulse would have a measured temperature excess of 0.2 to 0.3°F, a horizontal extent 300 to 900 ft, an excess dew point of 3 - 5°F, and a vertical velocity of 4 - 7 ft/sec. Together with these well-defined temperature pulses, there exist in this layer small bursts of temperature fluctuations of some 0.2°F. It may be that these phenomena are produced by the turbulent wakes of warm pulses rising through this region. Successive level runs at a given height indicate the presence of small groups or showers of such pulses.

The lapse rate in the intermediate layer is extremely variable, several stable layers being evident on any descent through the layer. These more stable regions are composed generally of isothermals or small temperature inversions, some 50 to 100 ft in vertical thickness, the temperature inversion being 0.5 to 1.0°F, and seem to be situated randomly in time and space. No explanation is offered for the formation of these more stable regions.

(c) The sub-cloud layer

Extending from cloud base and down some 200 to 400 ft there exists a more stable layer, usually composed of several thin layers of differing stabilities, a typical formation being isothermal-inversion-isothermal. The magnitude of the inversion is about 1.0 to 3.0°F. This region seems to increase in thickness and stability during a day of fair weather convection, which can be associated with a rising and flattening of cloud base.

Temperature pulses recorded at the bottom and at the top of this layer show a marked change in dew point excess. A typical pulse just below this layer will have a measured temperature excess of 0.3 to 0.4°F, a horizontal extent of 500 to 600 ft, an excess dew point of 4 to 6°F and a vertical velocity of 5 to 8 ft/sec. Above this transition level, the frequency of well-defined pulses drops off considerably. A typical pulse here would have a measured excess temperature of 0.3 to 0.4°F, a horizontal extent of 600 to 700 ft, an excess dew point of 1 to 2°F and a vertical velocity of 4 to 5 ft/sec.

A level run at any height through the sub-cloud layer would reveal the presence of long-wave temperature fluctuations, with a magnitude of the order of 1.0°F. These slow variations are attributed to two causes; first to the downward movement of air near a developing cloud, and second to some form of wave motion in the stratified layers themselves. Dry patches have been observed in a descent through this layer, which seems to support the first reason, whilst a similar fluctuation in the top of an inversion over the sea suggests the second reason.

Finally, very short pulses of temperature excess 0.2 to 0.3°F with horizontal extent of 100 ft or less are occasionally recorded, and are attributed to local condensation either in a rising bubble of warm air, or to the general mixing of air with different temperatures and dew points.

(d) Above and alongside clouds

Occasionally, positive pulses of temperature are found above cloud base. A typical pulse recorded at these levels would have a measured temperature excess of 0.2 to 0.5°F, a horizontal extent of 500 to 600 ft, an excess dew point of 1 to 2°F and would be moving upwards with a velocity of 2 to 3 ft/sec. It is possible that these pulses have their origins either in the sub-cloud layer or in a more stable region sometimes found at the sides of, or above, the clouds. Again, an analogy can be drawn with positive pulses observed above an inversion over the sea.

/Flying

Flying some 400 to 500 ft directly above small developing cumulus clouds, very rapid negative pulses of temperature are recorded (Fig. 12). These pulses give a sharp drop of some 3.0 to 4.0°F with a horizontal extent of 300 to 400 ft. No effort has been made to investigate these negative pulses fully, since they appeared on one flight only, and no explanation is offered as to their formation.

The bumps experienced by the aircraft and recorded by the accelerometer at these heights show a marked difference from those recorded at levels below cloud base. The recorded bumps take the form of small undulations rather than sudden jolts, and are probably due to gradual increases in vertical velocity rather than to well-defined rising bubbles.

10. Conclusions

When thermal convection was active over land, positive pulses of temperature were recorded from 500 ft to cloud base. The magnitudes and numbers of these pulses decreased suddenly between 500 ft and 1,500 ft but showed little change from 1,500 ft to cloud base. At all heights below cloud base, little variation was found in the average horizontal extent of these warm pulses. A few small positive pulses were also recorded above cloud base, though directly above developing cumuli well-defined negative pulses of temperature were obtained.

The vertical temperature profile of the air below cloud showed a region of stable air about 200-400 ft thick directly below cloud base. Several smaller layers of stable air about 100 ft thick were recorded at all levels down to 1,000 ft, though consecutive descents indicated that these layers were not permanent features.

The records from all sensitive instruments suggested a sub-division of the cloud to ground layer into three parts (Fig. 3). The dividing line between the "turbulent layer" and the "intermediate layer" was well defined, but the lower boundary of the "sub-cloud layer" was not easily observed.

A possible mechanism of convective cloud formation suggested by the above observations would be as follows. During the morning the rise of ground temperature, with differential heating of the surface, would cause bubbles of air to ascend and, if sufficiently moist, to form cloud. The sub-cloud layer would be established at the same time. Further ascent of air would warm and deepen this layer until no more bubbles of ground origin could reach cloud base directly. However, cloud formation could proceed by air breaking away from the top of the sub-cloud layer, and could continue long after the surface temperature is past its maximum. This would produce a flattening of the cloud base during the afternoon, and an extension of cloud formation beyond the limits deduced from surface temperature observations.

Acknowledgements

I would like to express my thanks to all the members of the Meteorological Research Flight for their assistance in obtaining flight records and in particular to Flt.Lt. Baker, M.B.E., D.F.C., and Flt.Lt. Bavin for the steadiness and accuracy of their flying, in conditions which were frequently uncomfortable.

References

1. Bunker, A.F. J.Met., 10, No. 3, June, 1953.

2. Bunker, A.F. Papers in Physical Oceanography and Meteorology, XII, No. 3, Dec., 1952.

3. Grant, D.R. M.R.P. 542, 1950.

4. Langwell, Patricia A. J.Met., 10, No. 3, June, 1953.

5. Ludlam, F.H. and Scorer, R.S. Q.J. Roy. Met. Soc., 79, No. 341, July, 1953.

6. Murgatroyd, R.J. and James, D.G. M.R.P. 804, 1953.

Table 1.

Flights and instruments used

Flight Number	Date	Time	Position	INSTRUMENTS: Ultra rapid thermometer	Hot wire anemometer	Directional hot wire anemometer	Auto-hygrometer	Type of flight
1	27. 6.52	10.30-12.30	Land	/	/			Level runs
2	30. 6.52	15.00-17.30	Land	/	/			Level runs
3	25. 8.52	10.30-12.30	Land	/	/	/		Level runs
4	25. 8.52	15.00-16.45	Land	/	/	/		Level runs
5	28. 8.52	10.30-12.30	Land	/	/	/		Level runs
6	29. 8.52	10.30-12.30	Land	/	/	/		Level runs
7	7.11.52	14.15-16.00	Land		/	/		Level runs
8	11.11.52	11.00-12.15	Land	/	/	/		Level runs
9	15.12.52	15.00-16.00	Land	/				Level runs
10	2. 2.53	14.15-16.15	Sea	/				Level runs
11	12. 3.53	14.45-16.00	Sea	/	/			Level runs
12	31. 3.53	15.00-16.30	Land	/	/			Level runs
13	23. 4.53	14.30-16.30	Land	/	/	/		Level runs, and descents
14	24. 4.53	14.30-16.30	Land	/	/	/		Level runs, and descents
15	28. 4.53	21.00-22.30	Land	/	/	/		Level runs
16	6. 5.53	11.45-13.00	Land	/	/	/		Descents
17 (a)	7. 5.53	14.40-17.00	Land	/	/	/		Descents
17 (b)	7. 5.53	14.40-17.00	Sea	/		/		Descents
18	11. 5.53	11.20-12.15	Land	/				Descents
19	12. 5.53	11.15-12.30	Sea	/				Descents
20 (a)	12. 5.53	15.00-17.30	Sea	/				Descents
20 (b)	12. 5.53	15.00-17.30	Land	/				Descents
21	28. 7.53	11.00-13.00	Land	/			/	Level runs, and descents
22	28. 7.53	15.20-17.00	Land	/			/	Level runs, and descents
23	26. 8.53	14.00-16.30	Sea	/			/	Level runs, and descents

Table 2. Observations over land.
Level flights only

Date	Time	Cloud base (ft)	Height (ft)	Mean T(°F)	Span (°F)	Mean F.P. (°F)	Span (°F)	Ultra rapid thermometer	Hot wire anemometer	Directional hot wire anemometer	Accelerometer
27. 6.52	10.30-) 12.30)	3,300	1,000	66.9	0.5	53	2	Many small fluctuations	Continuous gusts		Continuous bumps with max. of 0.25g
			1,700	63.0	0.5	51	2	Several square shaped pulses	Numerous fast gusts		Long quiet periods. Bumps to 0.20g max.
			2,400	59.4	0.4	50	2	Positive pulses	Small gusts		Long quiet periods. Bumps to 0.20g max.
30. 6.52	15.00-) 17.30)	3,400	400	69.9	1.1	62	2	Very many positive pulses up to 1.2°F with internal fluctuations of 0.5°F	Gusts up to 10ft/sec		Very many bumps up to 0.23g max.
			800	67.8	0.8	61	2	Very many positive pulses of up to 0.6°F	Gusts 5-8ft/sec		Many bumps to 0.15g
			1,200	64.6	0.6	60	1	Positive pulses 0.3-0.4°F	Gusts 5-7ft/sec		Bumps to 0.16g
			1,600	63.5	1.0	60	3	Several positive pulses of 0.3°F and one of 0.5°F	Gusts 4-5ft/sec		A few large bumps up to 0.20g
			2,000	61.3	1.1	58	2	Small bursts of positive pulses 0.2-0.3°F	A few gusts of 4-5ft/sec		
			2,400	59.0	1.0	59	1	Few small temperature fluctuations	Gusts 3-4ft/sec		
			3,500	59.1	0.6	46	2	Slow positive pulses of 0.5°F to 3.0°F	No gusts		
25. 8.52	10.30-) 12.30)	2,000 to 2,400	1,000	61.9	0.5	54	3	First part noisy with fluctuations of 0.3°F Second part has isolated pulses 0.2-0.3°F	Very many gusts up to 10ft/sec	Very many gusts up to 10ft/sec	Many bumps up to 0.17g
			1,500	59.2	0.8	52	2	Positive pulses from 0.2-0.3°F	Regions of 7-10ft/sec	Regional 7-10ft/sec	Well-defined bumpy regions up to 0.24g
			2,000	57.1	0.6	51	2	Positive pulses from 0.2-0.3°F	Well marked regions of 7-8ft/sec	Noisy 8-10ft/sec	Variable regions; bumps to 0.31g
			6,000	48.6	0.5	26	4	Slow long waves of 1.5°F	Small gusts of 1-2ft/sec	Quiet gusts 1-3ft/sec	No bumps
25. 8.52	15.00-) 16.45)	3,300	1,000	64.4	0.4	47	2	Long waves of 0.3-0.4°F. Positive pulses of 0.3°F	Continuous gusts of 4-5ft/sec	Continuous gusts, in general 4-5ft/sec but occasionally up to 8ft/sec	Continuous bumps up to 0.16g
			1,500	61.8	0.2	53	1	Long waves of 0.3°F. Positive pulses of 0.3°F	Well marked regions of 5ft/sec		Well-defined regions of bumps up to 0.20g
			2,000	59.3	0.4	54	2	Positive pulses of 0.3°F. One negative of 0.2°F	Regions of gusts up to 5ft/sec		Regions up to 0.20g
28. 8.52	10.30-) 12.30)	3,000	500	59.6	0.5	52	3	Continuous positive pulses of 0.8-1.2°F	Continuous gusts 4-5ft/sec and up to 10ft/sec	Continuous gusts of 4-5ft/sec. Some to 10ft/sec	Continuous bumps, with max. of 0.20g
			1,000	57.0	0.5	50	2	Few pulses of 0.3°F, isolated or in groups	Gusts 4-5ft/sec in regions	Well marked regions of gusts 4-5ft/sec	Regional. Up to 0.16g
			1,500	54.7	0.5	49	3	Few pulses of 0.2°F, isolated or in groups	Gusts of 3ft/sec with 4-5ft/sec at times	Regional. Gusts up to 6-7ft/sec	Regional. Up to 0.21g
			2,000	52.5	0.5	48	2	Isolated positive pulses 0.2-0.3°F	Regional gusts 4-5ft/sec		Regional. Up to 0.21g
			2,500	50.1	0.5	48	2	One slow negative of 0.4°F. Positive of 0.2-0.3°F	Regional gusts 4-5ft/sec		
			3,000	48.2	1.2	47	3	Slow negative changes of 1°F. Positive pulses of 0.4°F. Small bursts of 0.2°F	Regional 4-6ft/sec		
29. 8.52	10.30-) 12.30)	No low cloud	500	62.9	0.8	51	2	Continuous positive pulses of 0.7°F-1.0°F	Continuous gusts of up to 7ft/sec	Continuous gusts of 6-8ft/sec	Numerous bumps up to 0.16g
			1,000	60.9	0.7	52	1	Slight grouping. Positive pulses of 0.2-0.4°F	Numerous gusts 2-3ft/sec. Occasionally 5-6ft/sec	Regions of gusts 4ft/sec and also 6-7ft/sec	Slightly regional. Bumps to 0.21g
			1,500	58.3	0.7	51	1	Regions of positive pulses of 0.3°F	Continuous gusts 4-6ft/sec	Regions of gusts 5-6 ft/sec	Regional. Bumps to 0.18g
7.11.52	14.15-) 16.00)	3,800	1,000	41.6	0.4				Very many gusts 4-6ft/sec	Numerous small gusts 5ft/sec. Occasionally 6-7ft/sec	Very disturbed, with max. of 0.25g
			1,500	39.0	0.3				Generally quiet. Groups 3-4ft/sec	Regional, with gusts 4ft/sec and occasionally 6-8ft/sec	Isolated bumps of max. 0.20g
			2,000	36.5	0.4				Quiet. Sudden gusts to 5ft/sec	Quiet. Occasionally gusts 4-6ft/sec	Regional. Bumps to 0.13g
			2,500	33.9	0.4				Long-wave gusts 3-4ft/sec	Quiet. Sudden gusts 3-6ft/sec	
			3,000	30.3	0.4				Long waves of 3-4ft/sec		
11.11.52	11.00-) 12.15)	2,900	500	41.7	0.8	36		Very many positive pulses 0.6-0.8°F	Numerous fast gusts up to 6ft/sec	Numerous gusts, with max. of 8-10ft/sec	Very bumpy, up to 0.15g
			1,000	41.3	1.0	33		Small bursts of 0.2°F. Isolated pulses of 0.4°F	Numerous gusts up to 4-5ft/sec	Regional. Well-defined gusts up to 8ft/sec max.	Regional. Bumps to 0.18g
			2,800	32.0	0.8	30		Long waves of 0.5°F. Regions of 0.2°F fluctuations	Long-wave fluctuations, with occasional 2-3ft/sec gusts	Well-defined isolated gusts up to 5ft/sec	Regional. Bumps to 0.15g
15.12.52	15.00-) 16.00)	3,600	1,500	30.3				Very disturbed. Pulses 0.3-0.4°F. A few 0.6°F			Very bumpy. Bumps to 0.20g max.
			2,000	28.4				Many positive pulses of 0.4°F			A few bumps up to 0.20g
			2,500	26.2				Very quiet. A few positive pulses of 0.2°F			Regional. Some bumps to 0.20g
			2,900	24.6				Quiet. A few pulses of 0.2°F. Warm patch 0.3°F			A few bumps of 0.20g. Mainly 0.15g
			3,400	22.4				Long-wave fluctuations of up to 1.0°F. Regions of positive pulses of 0.4°F and calm			Few bumps of 0.10g. More 0.13g
			3,500	22.0				Long-wave fluctuations of 2°F, positive and negative changes. Few pulses (positive) of 0.3°F			Few bumps of 0.10g. More 0.13g
31. 3.53	15.00-) 16.30)	4,000	500	41.9	0.8			Overall change 1.6°F. Many positive pulses to 1.0°F	Very disturbed. Gusts to 8-10ft/sec		Many bumps. Some to 0.20g
			1,000	45.6	0.1			Overall change 1.4°F. Many positive pulses to 1.0°F	Very disturbed. Gusts 6-8ft/sec		Many bumps. Some to 0.20g
			1,500	38.8	0.1			Overall change 1.5°F. Few positive pulses to 0.6°F	Regional. Gusts of 6-7ft/sec		A few bumps to 0.10g
28. 4.53	21.30-) 23.00)	No low cloud	500	42.9	0.2			Very disturbed. Many positive pulses of up to 0.5°F in overall change of 0.9°F	Many gusts of 3-4ft/sec	Many gusts 2-3ft/sec	Many bumps from 0.10g-0.20g
			1,000	40.3	0.1			Numerous small pulses of 0.1°F in overall change of 0.3°F			Many bumps of 0.10g. A few to 0.20g
			2,000	36.3	0..						Only a few bumps of about 0.10g
			3,000	31.9							Very few undulations> 0.10g

Table 3.

Observations over sea. Level flights only

Date	Time	Cloud base (ft)	Height (ft)	Mean T. (°F)	Span (°F)	Mean F.P. (°F)	Span (°F)	Ultra rapid thermometer	Hot wire anemometer	Accelerometer
2. 2.53	14.45-16.15	3,200	500	38.3	0.5	25	1	Continuous fluctuations of 0.2°F. Slower change of 0.8°F		Continuous bumps up to 0.25g
			1,000	36.0	0.4	24	2	Small fluctuations of 0.2°F. Slow long-wave changes		Many bumps up to 0.16g
			2,000	31.5	0.3	23	2	A few slow positive pulses, 0.3-0.4°F		Regions of bumps up to 0.10g
			2,500	29.1	0.6	22	2	A few fast positive pulses of 0.4°F. Long cold pulses near edge of clouds		A few bumps up to 0.10g
12. 3.53	14.45-16.00	No low cloud	500	41.1	0.0			Very small positive pulses in overall change of 0.4°F	Long-wave changes mainly, but a few gusts of 2-3 ft/sec	Very few bumps greater than 0.10g, but maximum of 0.12g
			1,000	39.0	0.3			Many positive pulses of 0.3°F in overall change of 0.8°F	Some small gusts of 2-3 ft/sec	Very few bumps, but maximum of 0.25g
			1,500	36.8	0.2			Only positive pulse of 0.3°F	A few gusts of 2-3 ft/sec	Several bumps, with a maximum of 0.18g

Table 4. Observations on flights with the automatic hygrometer

Date	Time	Place	Cloud base (ft)	Height (ft)	Mean Temp. (°F)	Span (°F)	Mean F.P. (°F)	Span (°F)	Ultra rapid thermometer	Automatic hygrometer	Accelerometer
28. 7.53	11.00-13.00	Land	2,100	500	60.2	0.6	46	3	Numerous positive pulses up to 1.3°F, over 2,000 ft	Considerable variations up to 6°F, last mainly 4°F	Continuous bumps up to 0.30g
				1,000	57.7	0.3	45	2	A few positive pulses up to 0.6°F, over 2,000 ft	Many wet patches of 5°F. Considerable pulses 1°F	Bumps up to 0.25g, with a few quiet periods
				1,500	55.0	0.5	45	3	Long waves of 0.4°F over 4,000 ft. A few pulses of 0.3°F	No sharp pulses. Long-wave fluctuations of 4°F	Isolated bumps of 0.25g in long quiet periods
				2,000	52.6	0.6	43	4	Long-wave fluctuations of 0.5-0.7°F only	Long waves of 6°F and over. A few small 1°F pulses	Long quiet periods, with smooth bumps to 0.15g
28. 7.53	15.30-17.00	Land	3,000	500	63.0	0.9	48	3	Many positive pulses of 0.3-0.5°F. Sudden drop of 1.3°F	Many wet pulses of 3-4°F excess. Sudden dry patch of 4°F	Continuous bumps up to 0.25g
				1,000	62.0	1.2	45	4	A few positive pulses of 0.2-0.3°F. Sudden drop of 1.0°F	Long waves of 6°F. Peaks of 2-3°F excess	Isolated bumps to 0.25g
				1,500	58.3	1.1	44	4	A few positive pulses of 0.2-0.3°F. Sudden drop of 0.5°F over 5,000 ft	Long waves of 6°F. Isolated pulses of 2-3°F excess	Isolated bumps to 0.17g
				2,000	55.7	0.9	44	5	Numerous positive pulses of 0.4°F over 1,200 ft	A few pulses of 6°F excess. Slow dry patches of 4°F	Isolated bumps to 0.25g
				2,500	53.4	0.9	44	5	Long wave of 1.0°F. A few positive pulses of 0.3°F over 800 ft	Well marked group of wet pulses of 1-2°F excess	Isolated bumps to 0.15g
				3,000	50.8	0.8	42	4	A few small fluctuations of 0.3°F over 1,000 ft	One group of wet pulses of 1-2°F excess. Slow dry patch of 2°F	

Date	Time	Place	Cloud base (ft)	Height (ft)	Mean Temp. (°F)	Span (°F)	Mean F.P. (°F)	Span (°F)	Ultra rapid thermometer	Automatic hygrometer	Accelerometer
26. 8.53	14.00-16.30	Sea	4,500	100	63.2	0.2	53	2	Very many fast positive pulses of 0.5°F over 100 ft	Wet pulses of 2-3°F excess. Wet patch of 2°F over 5,000 ft	
				500	62.4	0.3	50	1	A few positive pulses of 0.3-0.5°F over 100 ft	Series of wet pulses of 2°F excess, over 1,000 - 1,500 ft	
				1,000	60.0	0.7	47	3	One region of fluctuations of 0.4°F. Long waves of 0.5°F	Eight wet pulses of 4-5°F excess, with spacing of 4,500 - 5,000 ft	
				2,000	56.2	0.3	44	2	A few bursts of small fluctuations of 0.2-0.3°F	Three wet pulses of 2°F, lasting 300 ft - 2,500 ft	
				3,000	51.3	0.5	41	3	A few fluctuations of 0.2°F. Long wave of 0.5°F over 6,000 ft	No well-defined pulses. Change of 5°F in ambient F.P.	

Table 5

Height (ft)	Total bumps per min	Average maximum of all bumps (g)	Average duration of all bumps (ft)	Average mean of all bumps (g)	Average area of all bumps	Turbulence index
2,500	3.2	0.12	510	0.06	30.6	16.4
2,000	4.4	0.13	560	0.07	39.2	28.8
1,500	4.6	0.13	520	0.08	41.6	32.1
1,000	6.2	0.13	520	0.07	36.4	37.3
500	6.1	0.12	480	0.07	33.6	34.1

Table 6

23.4.53. 14.30-16.30. Flight 13. Land. No low cloud

Instruments:- Ultra Rapid Thermometer, Hot Wire Anemometer, Directional Hot Wire Anemometer, Accelerometer.

Flight details:- Level runs at 500 ft, 1,000 ft, 2,500 ft and 5,000 ft with all instruments. Slow descent from 5,000 ft to 500 ft using the Ultra Rapid Thermometer.

Height (ft)	Details from level runs	Details from descent
5,000	No temperature fluctuations or gusts recorded. Overall temperature change 0.3°F	
4,000		A few positive pulses of 0.4°F
		3,500 ft
3,000		
2,500	Well-defined regions of temperature fluctuation, up to 0.6°F in overall change of 1.1°F. Gusts of 3-4 ft/sec, giving smooth bumps up to 0.15g maximum	Considerable temperature fluctuations, with variations of up to 0.8°F
2,000		
		1,500 ft
1,000	Numerous fast positive pulses, giving gusts 6-10 ft/sec. Continuously bumpy, with bumps up to 0.25g	Many positive pulses of 0.5°F increasing at lower levels to 1.0°F
500	Continuous temperature fluctuation, with pulses of 0.7°F in overall change of 1°F. Gusts, very numerous, from 7-10 ft/sec and continuous bumps to 0.30g	

Table 7

24.4.53. 14.30-16.30. Flight 14. Land. No low cloud

Instruments:- Ultra Rapid Thermometer, Hot Wire Anemometer, Directional Hot Wire Anemometer, Accelerometer.

Flight details:- Level runs at 500 ft, 1,000 ft, 2,000 ft, 3,000 ft, 5,000 ft, followed by a slow descent from 5,000 to 500 ft, using the Ultra Rapid Thermometer.

Height (ft)	Mean T (°F)	Details from level runs	Details from descent
5,000	38.2°F	No fast temperature fluctuations or gusts. A few slow small changes visible	Very quiet. Long wave temperature fluctuations
4,000	42.5°F		3,900 ft Turbulent region. Fluctuations of 0.5-1.0°F
3,000	46.9°F	Top of haze layer. Very few temperature fluctuations in overall change of 0.7°F, with gusts 3-4 ft/sec, bumps less than 0.1g	2,500 ft 48.5°F Isothermal layer. Temperature fluctuations of 0.3°F 2,200 ft 48.5°F
2,000	50.6°F	A few positive pulses of 0.4°F in overall change of 1.5°F. Gusts of 4-6 ft/sec, with well-defined bumps to 0.25°F	1,900 ft Some positive pulses of 0.5°F, becoming up to 1.0°F in lower levels
1,000	55.9°F	Numerous pulses of all sizes, with maximum temperature excess 0.6-0.7°F. Gusts 6-8 ft/sec, almost continuous; many bumps greater than 0.20g	
500	58.3°F	Very many pulses of 0.8°F in overall change of 1.5°F. Continuously gusting up to 8-10 ft/sec, with bumps up to 0.25g	

Table 8

6.5.53. 11.45-13.00. Flight 16. Land. Cloud base 3,250 ft - 3,400 ft

Instruments:- Ultra Rapid Thermometer, Hot Wire Anemometer, Directional Hot Wire Anemometer, Accelerometer.

Flight details:- One descent from 4,250 ft to 500 ft using the Ultra Rapid Thermometer, followed by two other descents from 5,500 ft - 500 ft using the Hot Wire Anemometer and Directional Hot Wire Anemometer in turn.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
5,500	41.7	0.3	
			A few positive temperature pulses of 0.3°F A few gusts of 3 ft/sec All bumps less than 0.10g
3,250	49.3	0.8	Cloud base
3,140			Isothermal. Long-wave fluctuations of 0.8°F. Gusts 4-5 ft/sec. All bumps less than 0.10g
3,050 ft			
3,000	50.0	0.6	Very fast inversion of 3°F. Positive pulses of 0.5°F, with 5 ft/sec gusts and bumps up to 0.10g
2,900 ft			
2,750	51.1	0.7	Isothermal. Pulses up to 0.5°F; gusts up to 5 ft/sec. Few bumps, but one up to 0.20g
			Numerous positive pulses of temperature, 0.3°F generally, but up to 0.8°F at times. Gusts isolated and well marked 4-8 ft/sec. Bumps 0.1g-0.3g. All becoming less numerous at the lower levels
1,000	59.2	0.6	
			Traces suddenly becoming very disturbed
500	61.8	0.4	

Table 9

7.5.53. 14.40-17.00. Flight 17a. Land. Trace of cloud at 3,000 ft

Instruments:- Ultra Rapid Thermometer, Directional Hot Wire Anemometer, Accelerometer.

Flight details:- Two slow descents from 5,200 ft to 500 ft, using the Ultra Rapid Thermometer and Directional Hot Wire Anemometer in turn.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
5,200	39.5	1.5	↑ A few random isolated positive pulses of up to 0.4°F, with gusts of 3 ft/sec but no bumps greater than or equal to 0.1g ↓
3,600	39.9	0.9	↑ Inversion of 4.0°F. Large positive pulses of up to 2.0°F ↓
3,200	40.0	0.6	↑ Gusts up to 10 ft/sec. Bumps 0.1g but some 0.2g
3,000	39.6	0.6	↓ Small clouds
2,750	41.4	0.1	↑ Isothermal. Numerous small temperature fluctuations of 0.3°F, gusts of up to 5-6 ft/sec, and bumps up to 0.15g ↓
			↑ Positive pulses of 0.4°F to 0.6°F. Gusts of 3-4 ft/sec in general, but occasionally one of 8-10 ft/sec. Bumps up to 0.20g, corresponding to arrival of temperature pulse or gust. All the above in regions ↓
500	52.8	0.6	

Table 10

7.5.53. 14.40-17.00. Flight 17b. Sea. No low cloud

Instruments:- Ultra Rapid Thermometer, Directional Hot Wire Anemometer, Accelerometer.

Flight details:- Two descents made from 5,000 ft to 500 ft, using the Ultra Rapid Thermometer and Directional Hot Wire Anemometer in turn.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
5,000	39.6	0.6	
4,320	41.2	0.6	↑ Small inversion of 0.3°F, with fluctuations of the same order, and gusts 3ft/sec. Bumps less than 0.1g ↓
4,250	41.8	0.5	↑ Long slow inversion of 3°F, becoming ragged at 3,400 ft Small positive temperature fluctuations, with little gusts, and bumps less than 0.1g ↓
3,000	41.1	1.5	↑ A few small positive pulses of temperature Small gusts Bumps less than 0.1g ↓
500	46.0	0.1	

Table 11

11.5.53. 11.20-12.15. Flight 18. Land. Trace of cloud between 4,000 ft and 4,200 ft

Instruments:- Ultra Rapid Thermometer, Accelerometer.

Flight details:- Three slow descents from 5,500 ft to 500 ft using the Ultra Rapid Thermometer, starting from the same land position, along the same heading.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
5,000	31.6	0.6	Minor inversion, where position and magnitude vary with time from 0.8 to 2.0°F
4,850 ft			A few positive pulses up to 1.0°F. Little bumpiness. Passing over the tops of clouds gives fast negative pulses of 3-4.0°F
4,200	33.7	0.6	Small clouds
			Almost isothermal lapse rate. Positive pulses of 0.3°F to 1.2°F
3,800	34.0	0.1	
			Positive pulses of temperature, in general 0.3-0.7°F, but a few of 1.0°F Random positions in time, but usually in groups of 2 or 3 Several temporary inversions of up to 0.5°F and isothermals, whose positions and magnitudes vary with time
1,200	47.9	0.2	
			Very many positive pulses. In general 0.5°F but increasing in size towards the ground, and reaching 2 to 3°F
500	50.4	0.4	

Table 12

12.5.53. 11.15-12.30. Flight 19. Sea. No low cloud

Instruments:- Ultra Rapid Thermometer and Accelerometer.

Flight Details:- Three descents made in turn from 6,250 ft to 250 ft, using the Ultra Rapid Thermometer.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
6,200	31.2	0.2	
6,000	32.0	0.3	6,000 ft ↑ Well marked region of temperature fluctuations. Also, well-defined smooth bumps to 0.25g ↓ 5,250 ft
5,900 ft ↑ Minor temperature fluctuations on all descents of 0.3°F, with small inversions ↓ 5,700 ft			
5,800	32.6	0.4	
5,250	39.5	0.2	
			Random positive pulses of temperature of 0.4-0.5°F Minor bumps, less than 0.1g in general, but some up to 0.17g Random temporary minor isothermals and inversions of about 0.5°F, over approximately 100 ft vertical thickness
800	50.9	0.2	
500	51.4	0.4	
250	49.7	0.1	Complex inversion of 1.8°F on all descents. Very many positive pulses of temperature, up to 0.8°F below the inversion. Becoming isothermal

Table 13

12.5.53. 15.00-17.30. Flight 20a. Sea. No low cloud

Instruments:- Ultra Rapid Thermometer, Accelerometer.

Flight details:- Two descents made from 6,000 ft to 500 ft using the Ultra Rapid Thermometer.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
6,000	36.6	0.4	
5,750	36.8	0.8	5,800 ft ↑↓ Small inversion shown on both descents, though magnitude changes from 1°F to 1.5°F 5,600 ft
3,250	47.2	0.3	3,300 ft ↑↓ Small inversion of 0.4°F. Small positive pulses 3,200 ft
			A few positive pulses of 0.4°F, with bumps to 0.10g Small temporary inversions at random levels of magnitudes up to 1.0°F
750	55.0	0.0	
500	54.8	1.2	Inversion of 4.8°F, varying in thickness Large positive pulses underneath inversion, up to 0.7°F

Table 14

12.5.53. 15.00-17.30. Flight 20b. Land. Cloud base 4,000 ft

Instruments:- Ultra Rapid Thermometer and Accelerometer.

Flight details:- Two descents made from 6,500 ft to 1,000 ft using the Ultra Rapid Thermometer.

Height (ft)	Mean T (°F)	Span (°F)	Details from descents
6,500	35.6	0.6	
6,350			Isothermal. Well marked layer of temperature fluctuations, up to 0.7°F
6,070			
6,000	36.3	0.7	Well-defined region of temperature fluctuations of 0.8-1.5°F
5,500	37.6	0.6	Positive pulses of 0.3-0.5°F Isolated
4,000	44.0	0.6	Cloud base
			Pulses increasing in frequency and becoming larger with temperature excess of up to 1.0°F at lower levels
1,000	59.0	0.0	

Table 15

28.7.53. 11.00-13.00. Flight 21. Land. Cloud base 2,100 ft

Instruments:- Ultra Rapid Thermometer, Accelerometer and Automatic Hygrometer.

Flight details:- Level runs at 500 ft, 1,000 ft, 1,500 ft and 2,000 ft. Two slow descents from 2,000 ft to 500 ft using the Ultra Rapid Thermometer and Automatic Hygrometer in turn.

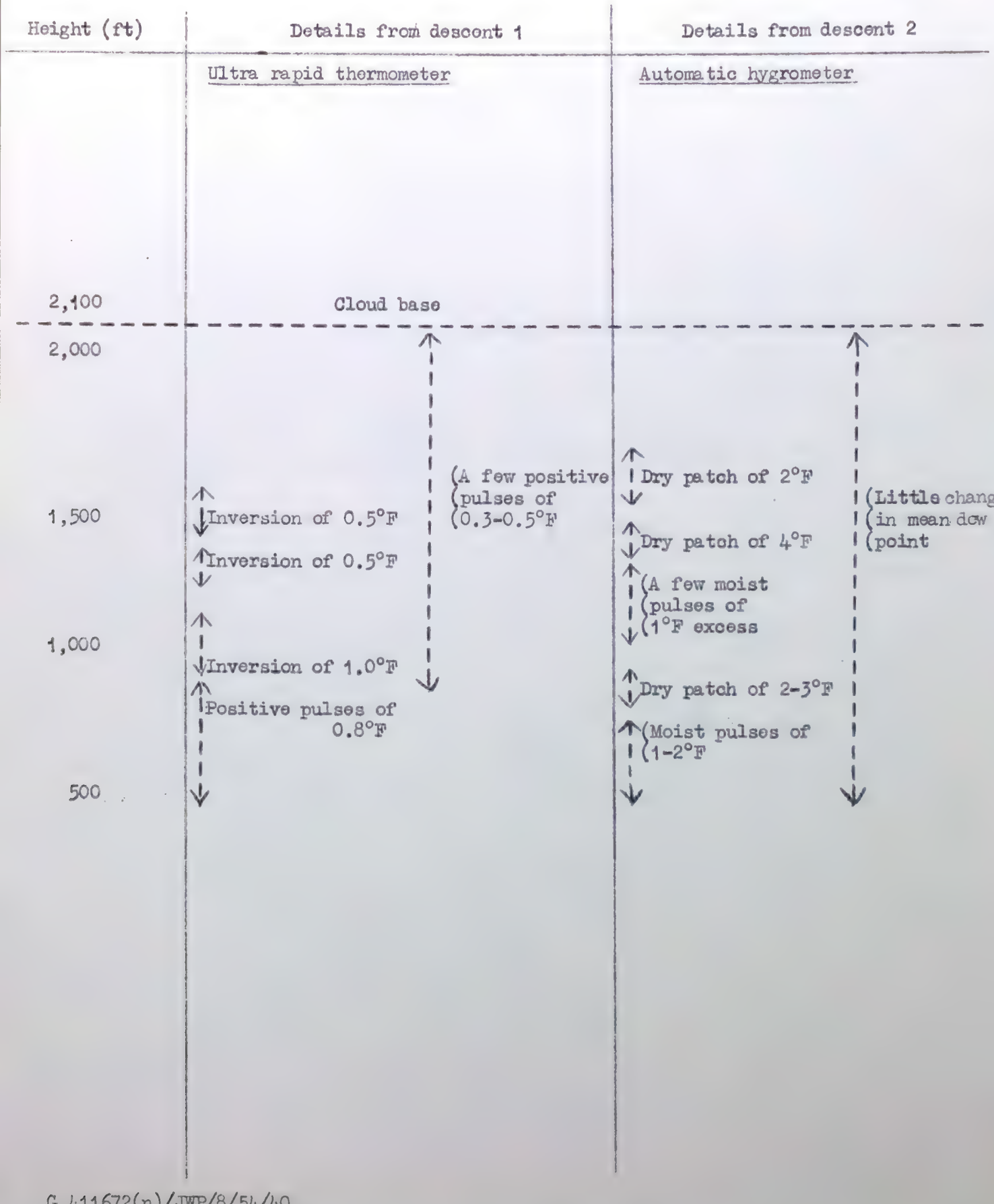


Table 16

26.8.53. 14.00-16.30. Flight 23. Sea. Cloud base 4,500 ft

Instruments:- Ultra Rapid Thermometer, Accelerometer and Automatic Hygrometer.

Flight details:- Level runs at 100 ft, 500 ft, 1,000 ft, 2,000 ft, 3,000 ft using Ultra Rapid Thermometer and Automatic Hygrometer. Slow descent from 4,000 ft to 1,000 ft using Ultra Rapid Thermometer.

Height (ft)	Details from level runs				Details from descent
	Mean T (°F)	Span (°F)	Mean F.P.(°F)	Span °F	
4,500	Cloud base				
4,000					
3,000	51.3	0.5	41	3	
	A few fluctuations of 0.2°F. Slow long-wave changes of 0.5°F over 6,000 ft No well-defined pulses. Considerable change of 5°F in ambient F.P.				(Lapse rate varying (from dry adiabatic to (almost isothermal.
2,000	56.2	0.3	44	2	(A few fluctuations (seen at all heights (of 0.2-0.5°F
	A few bursts of small temperature fluctuations of 0.2-0.3°F Three wet pulses of 2°F, lasting 300 ft to 2,500 ft				
1,000	60.0	0.7	47	3	
	One region of small fluctuations of 0.3-0.4°F Long waves of 0.5°F. Eight wet pulses of 4-5°F excess, with spacing of 4,500-5,000 ft				Sudden inversion of 1.0°F at 800 ft
500	62.4	0.3	50	1	
	A few positive temperature pulses of 0.3-0.5°F over 1,000 ft. Series of wet pulses of 2°F excess, over 1,000-1,500 ft				(Very many temperature (pulses of 0.3-0.6°F in (dry adiabatic lapse rate
100	63.2	0.2	53	2	
	Very many fast pulses of temperature of 0.5°F over 100 ft. Moist pulses of 2-3°F excess. Wet patch of 2°F, in 5,000 ft				

Frequency of bumps recorded on occasions when cloud base was at least 3000 feet

Fig. 1 Over land

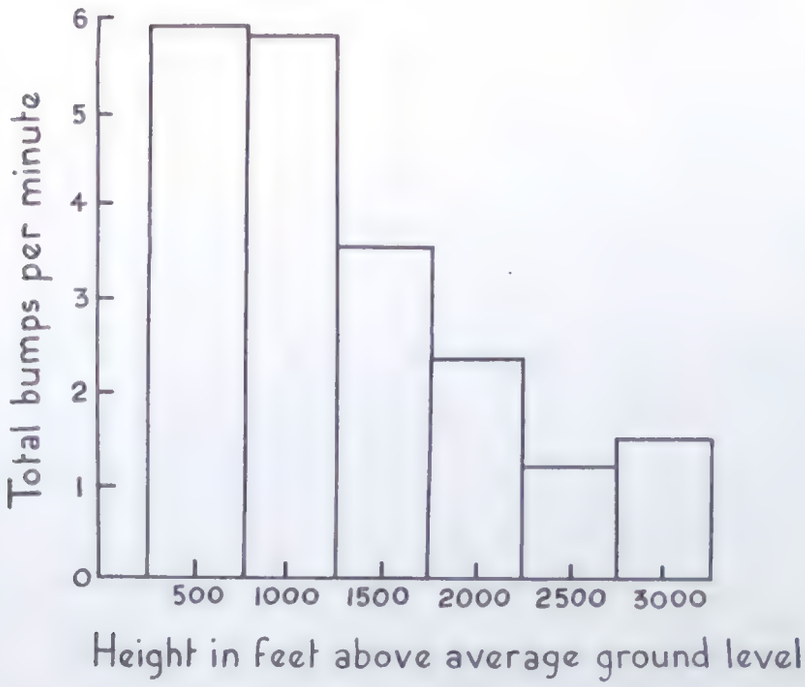
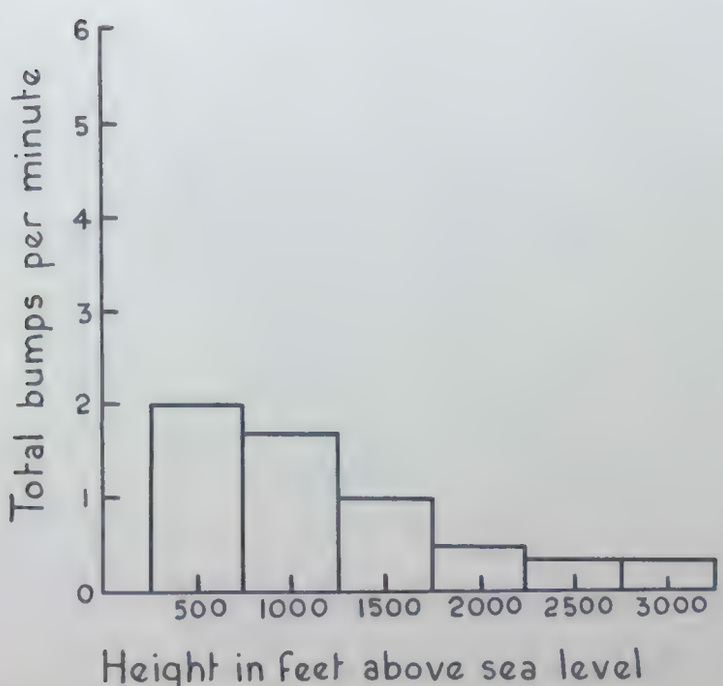


Fig. 2 Over sea



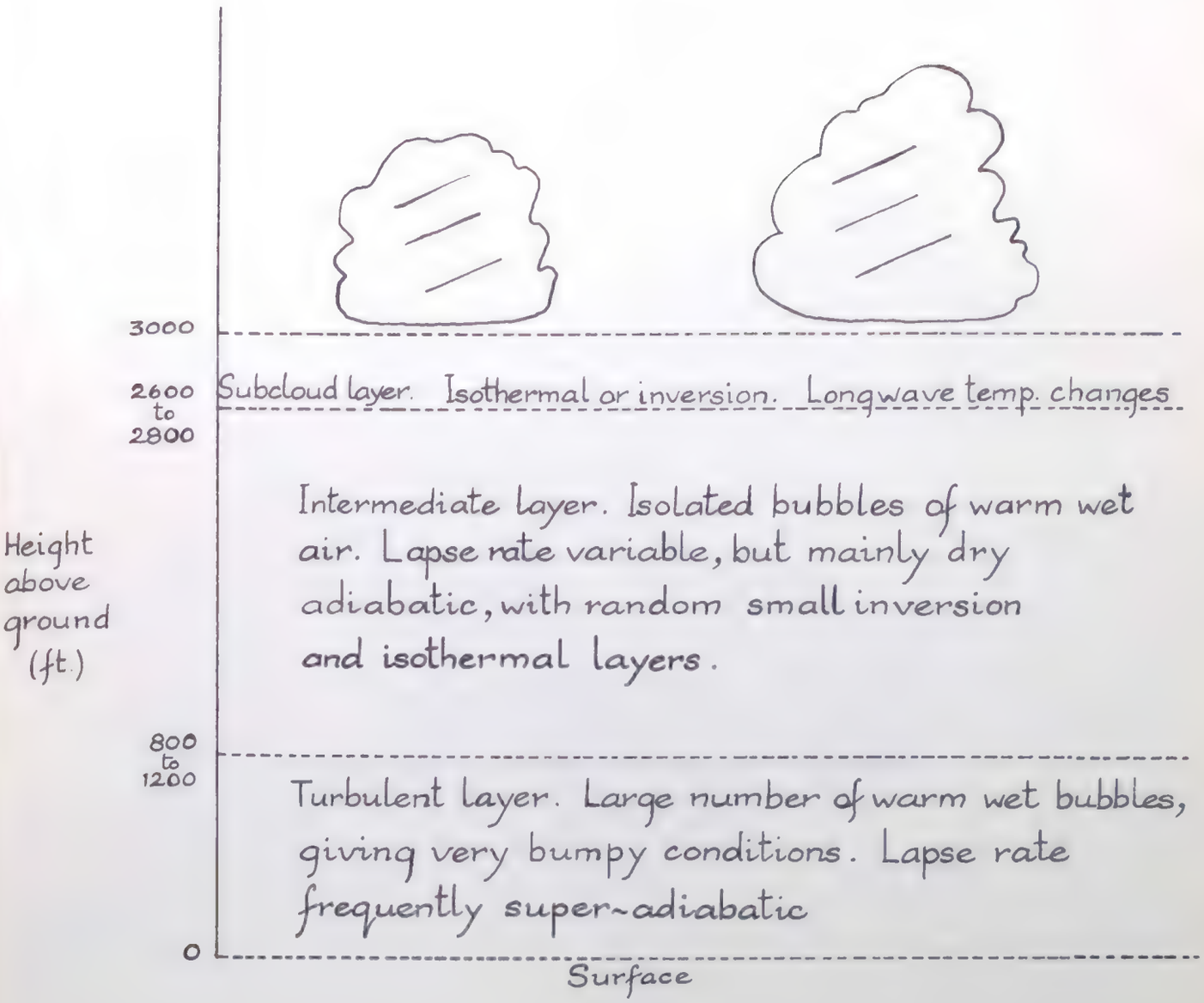
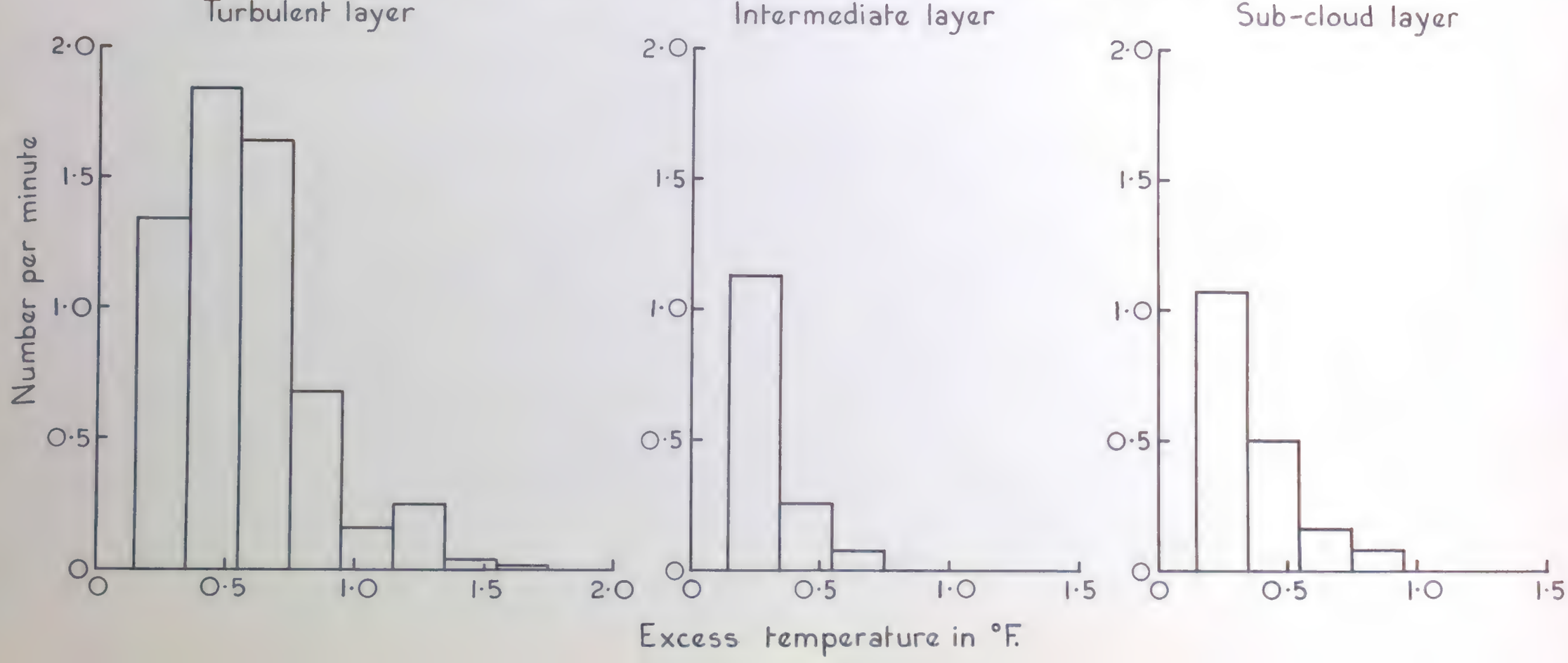


Fig. 3

Typical sub-divisions of region from ground to cloud base

Fig. 4

Frequency of temperature pulses recorded on level flights over land



M.R.P. 875

Fig. 5

Frequency of horizontal extents of temperature pulses recorded on level flights over land

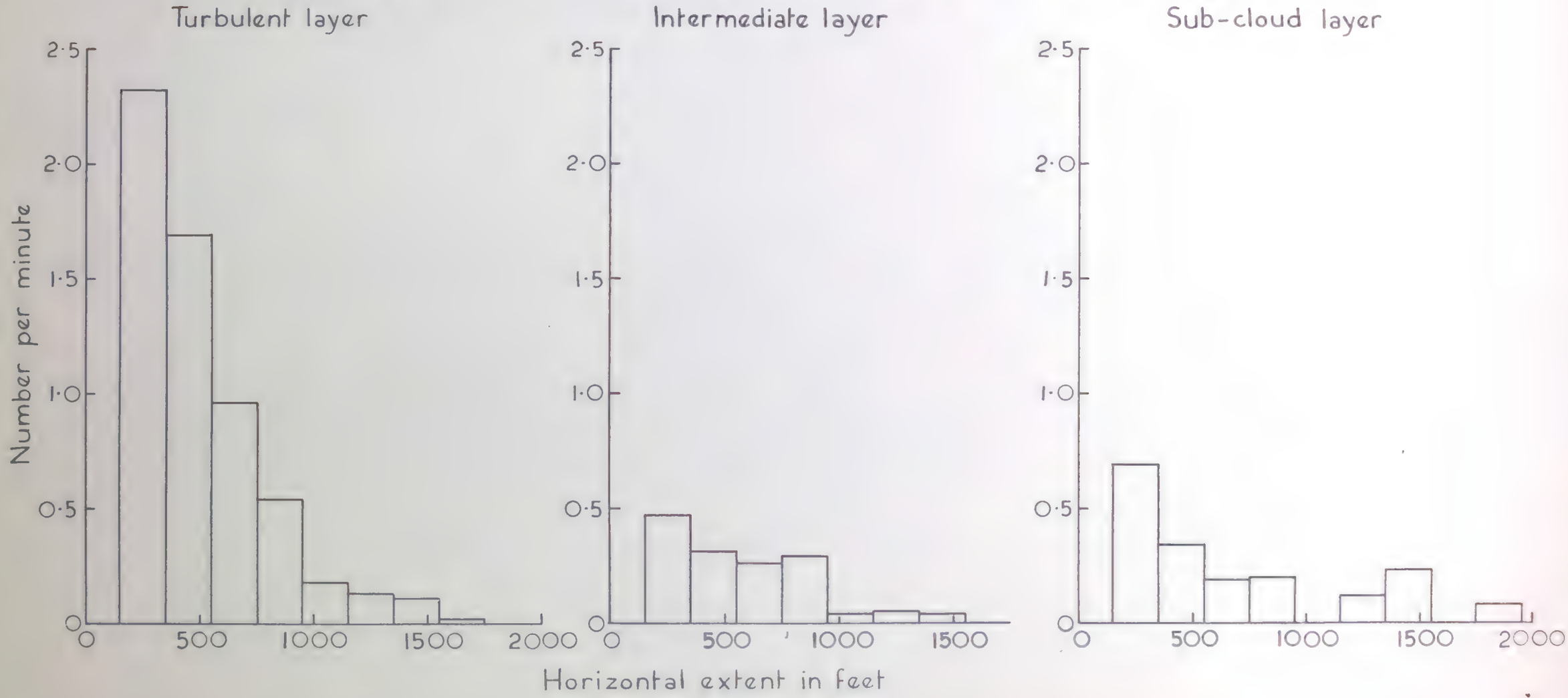


Fig. 6

Frequency of gust intensity recorded on level flights over land

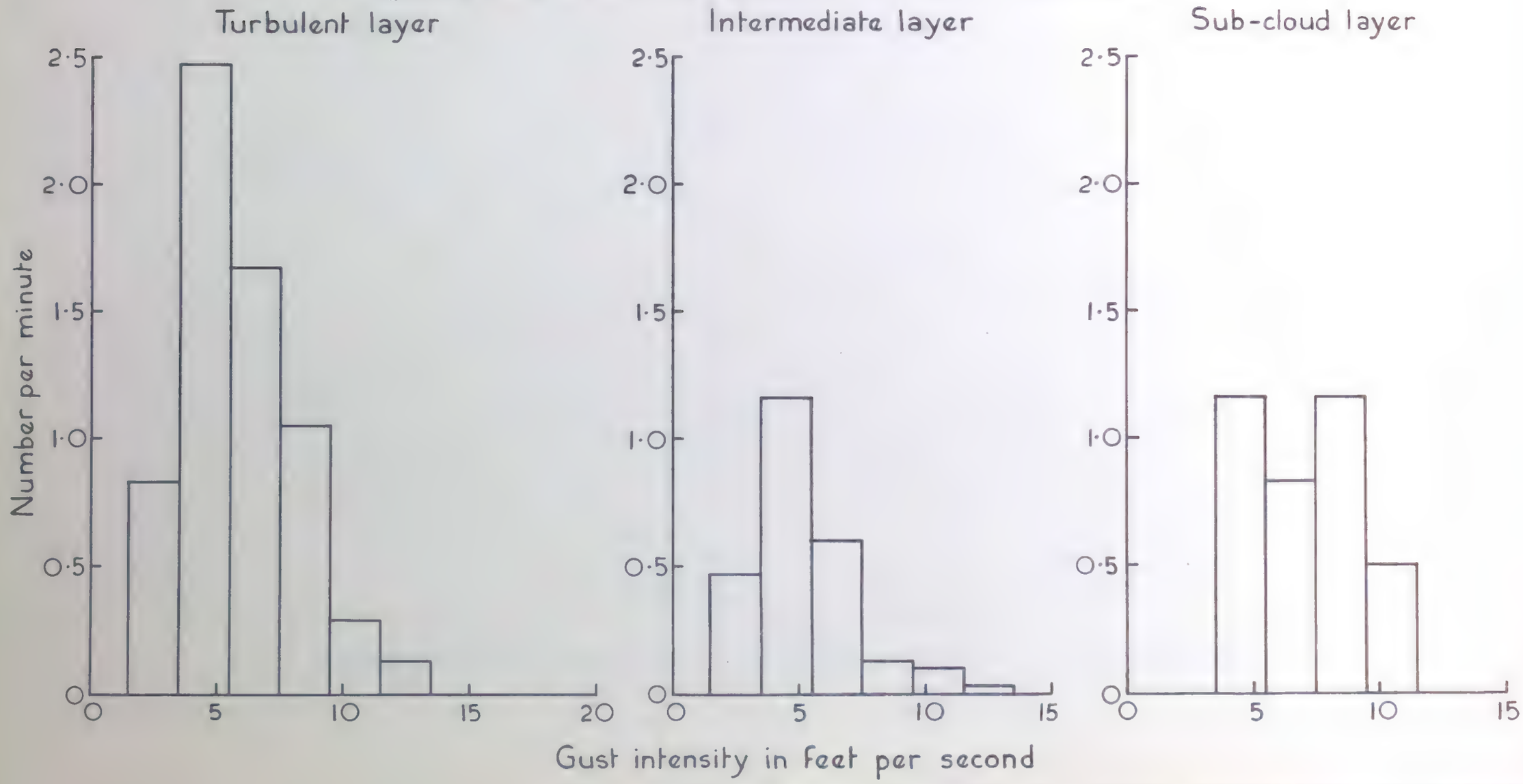


Fig. 7

Frequency of horizontal extent of gusts recorded on level flights over land

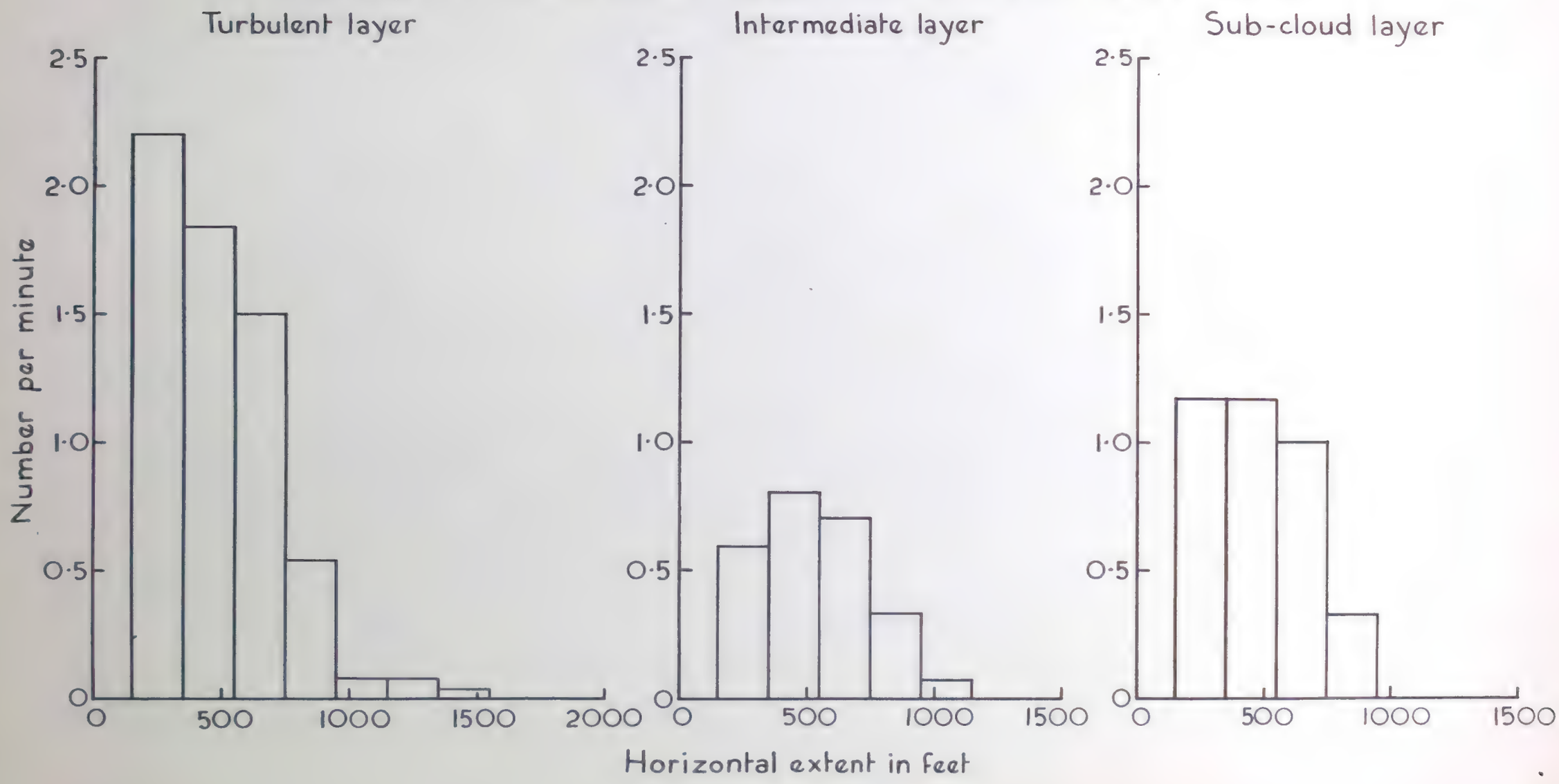


Fig. 8

Percentage of horizontal runs of 36,000 ft. where total temperature variation exceeds a given value

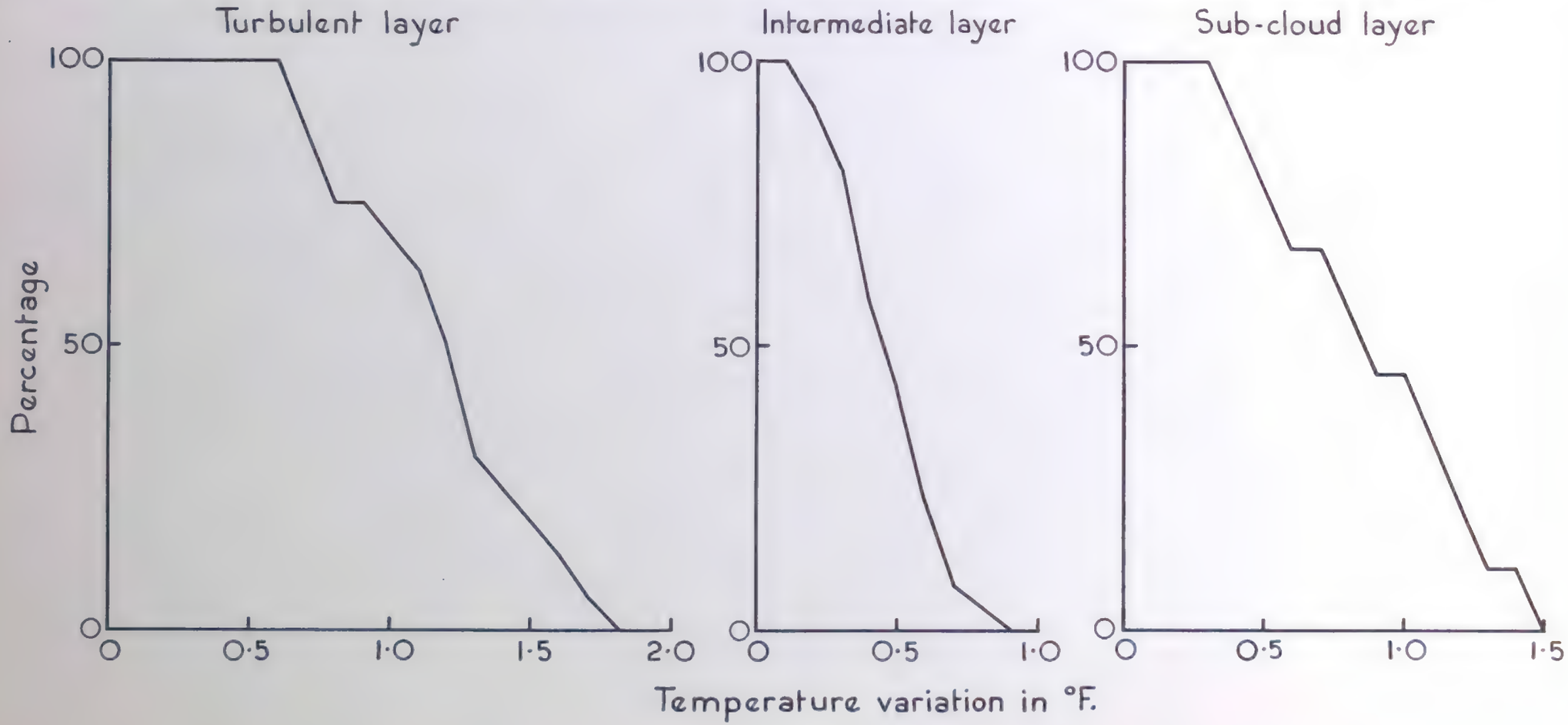
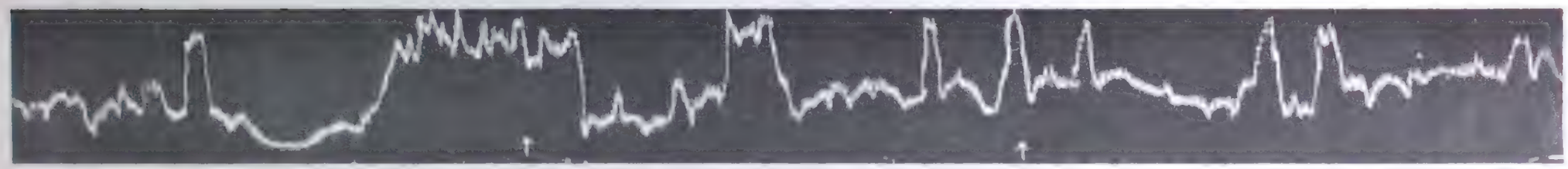


Fig. 9

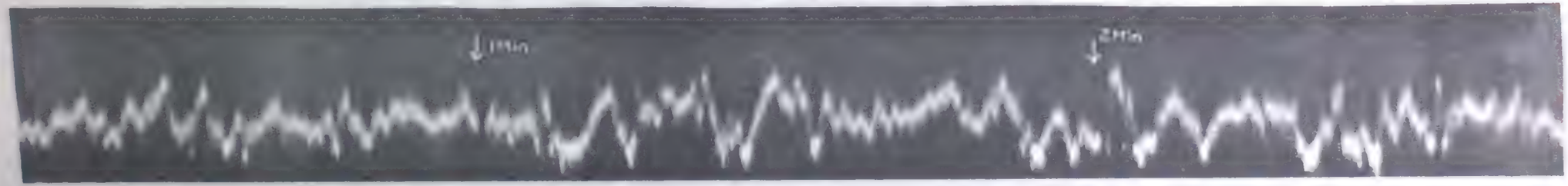
TURBULENT LAYER OVER LAND

M.R.P. 875

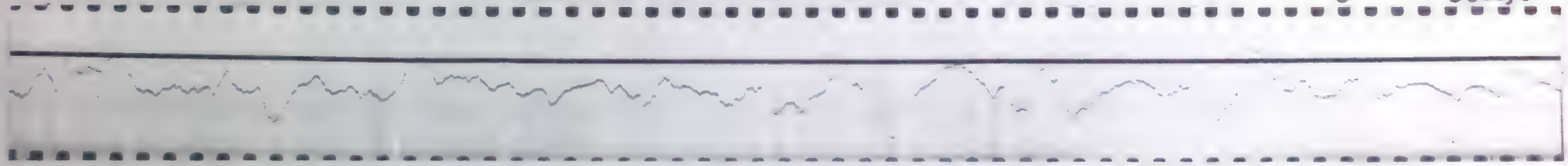
FLIGHT 5 500 FEET ULTRA RAPID THERMOMETER



FLIGHT 8 500 FEET DIRECTIONAL HOT WIRE ANEMOMETER



FLIGHT 21 500 FEET ACCELEROMETER



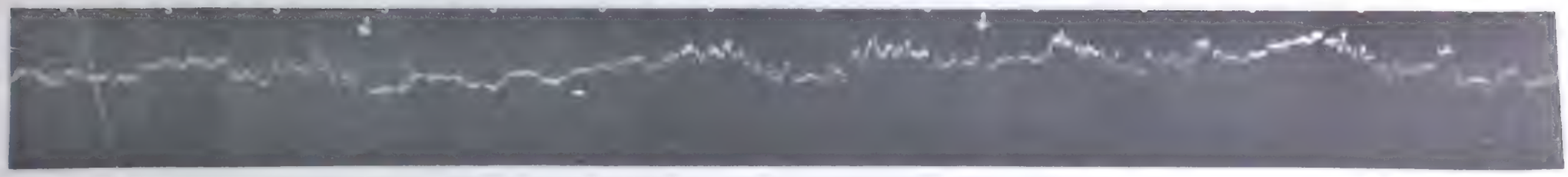
FLIGHT 21 500 FEET AUTOMATIC HYGROMETER

Fig. 10

INTERMEDIATE LAYER OVER LAND

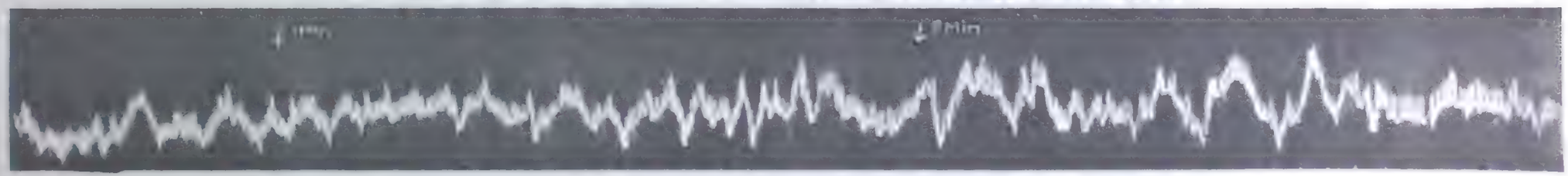
M.R.P 875

FLIGHT 3 1500 FEET ULTRA RAPID THERMOMETER



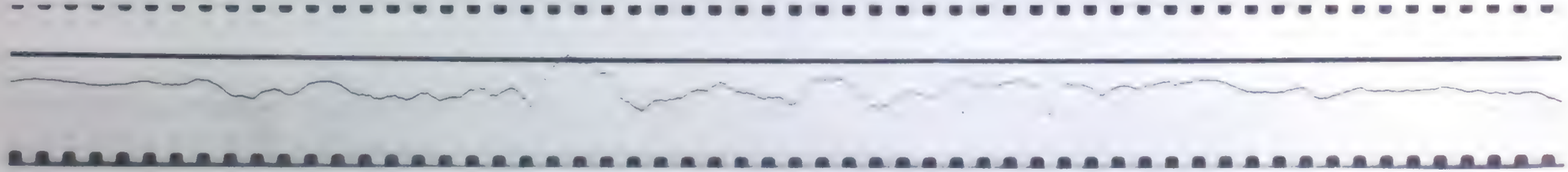
FLIGHT 7 1500 FEET DIRECTIONAL HOT WIRE ANEMOMETER

0 3000ft



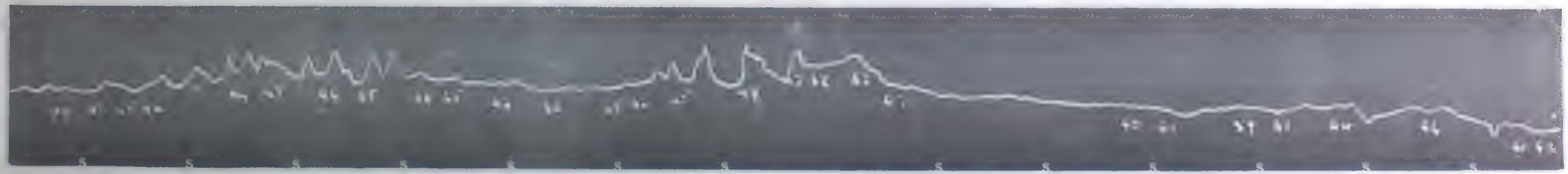
FLIGHT 22 2000 FEET ACCELEROMETER

0 3000ft



FLIGHT 22 2500 FEET AUTOMATIC HYGROMETER

0 1400ft



0 3000ft

Fig. 11

THE SUB-CLOUD LAYER OVER LAND

M.R.P. 875

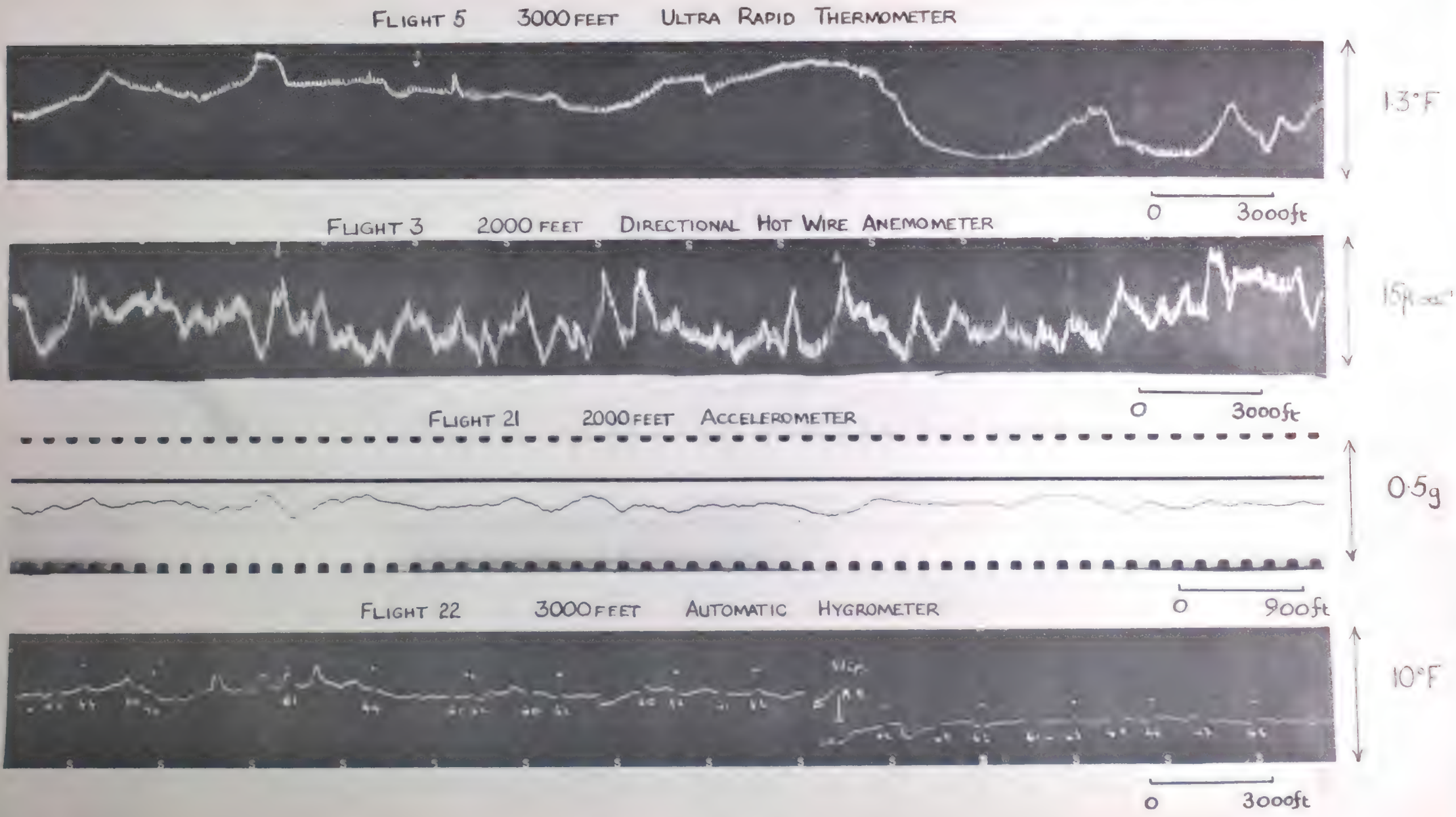
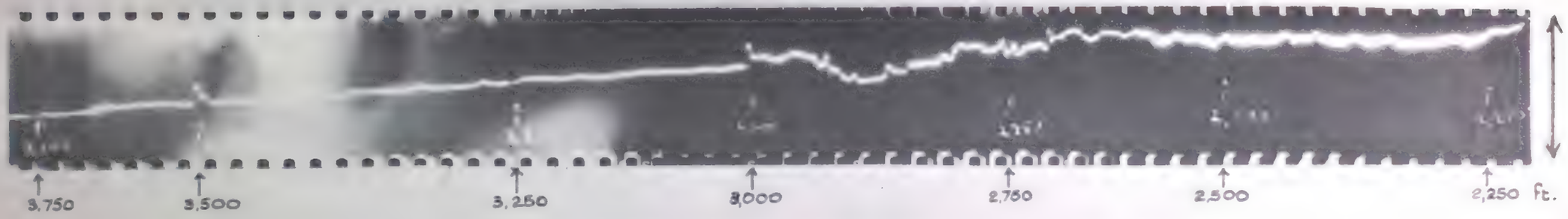


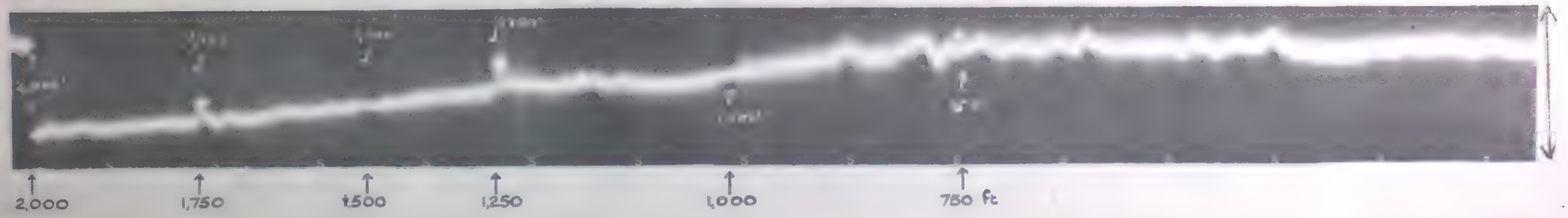
Fig. 12 SLOW DESCENTS OVER LAND USING THE ULTRA RAPID THERMOMETER

M.R.P. 875

FLIGHT 16 SHEWING SUB-CLOUD LAYER FROM 3000' TO 2800'



FLIGHT 18 SHEWING ONSET OF TURBULENCE AT 850 FEET



FLIGHT 18 SHEWING NEGATIVE TEMPERATURE PULSES ABOVE CLOUD

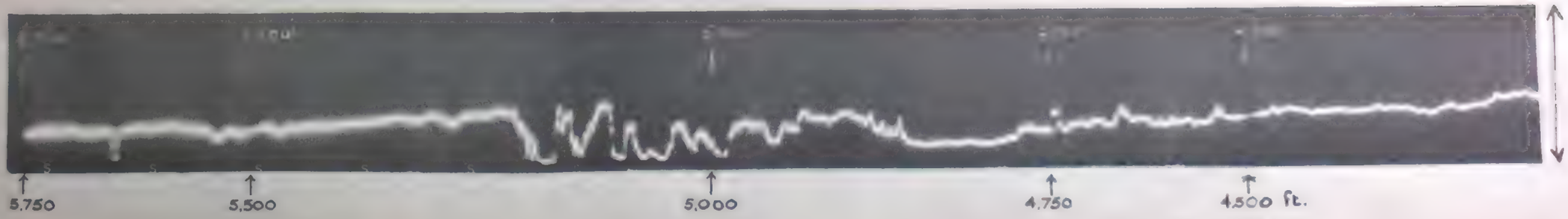
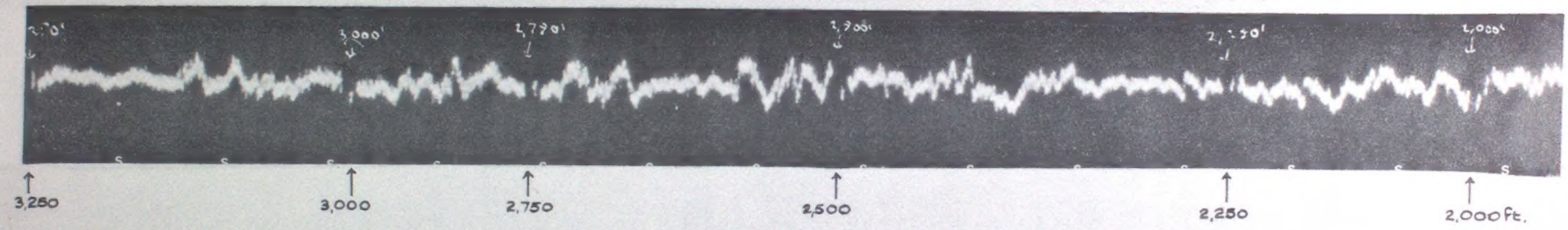


Fig. 13

SLOW DESCENTS OVER LAND

M.R.P. 875

FLIGHT 16 DIRECTIONAL HOTWIRE ANEMOMETER FROM CLOUD BASE



FLIGHT 21 AUTOMATIC HYGROMETER FROM CLOUD BASE

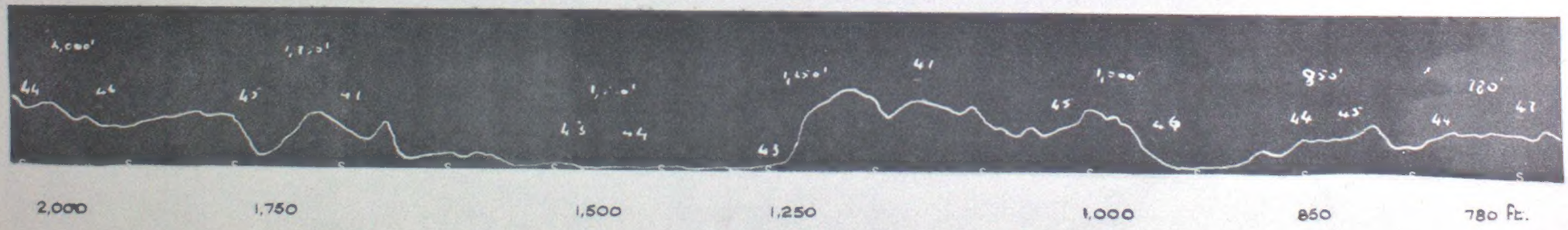


Fig. 14

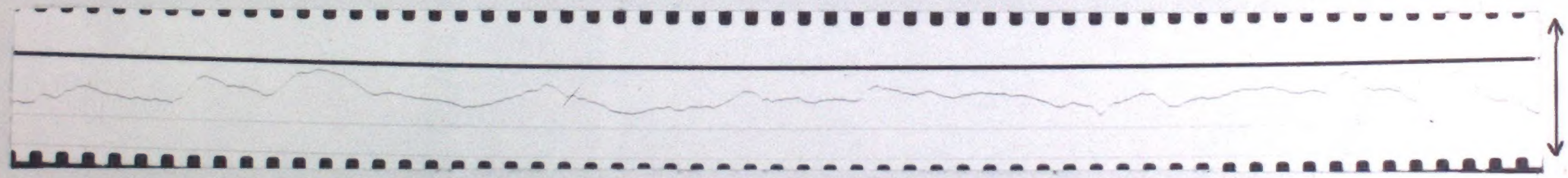
BELOW INVERSION OVER SEA

M.R.P. 875

FLIGHT 23 100 FEET ULTRA RAPID THERMOMETER

0 3000ft

FLIGHT 10 500 FEET ACCELEROMETER



0 900ft

FLIGHT 23 100 FEET AUTOMATIC HYGROMETER

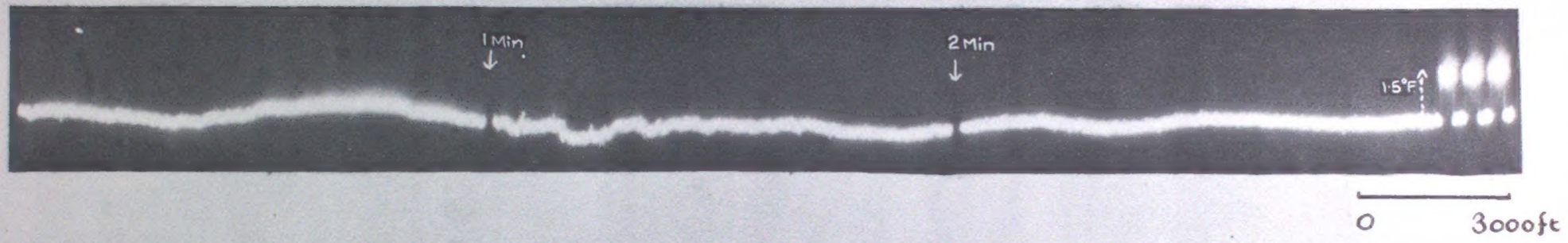
0 3000ft

Fig. 15

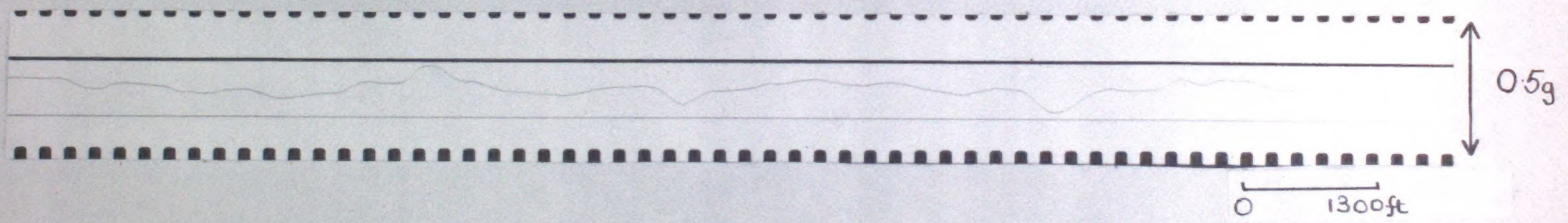
ABOVE INVERSION OVER SEA

M.R.P. 875

FLIGHT 10 1000 FEET ULTRA RAPID THERMOMETER



FLIGHT 11 1500 FEET ACCELEROMETER



FLIGHT 23 1000 FEET AUTOMATIC HYGROMETER

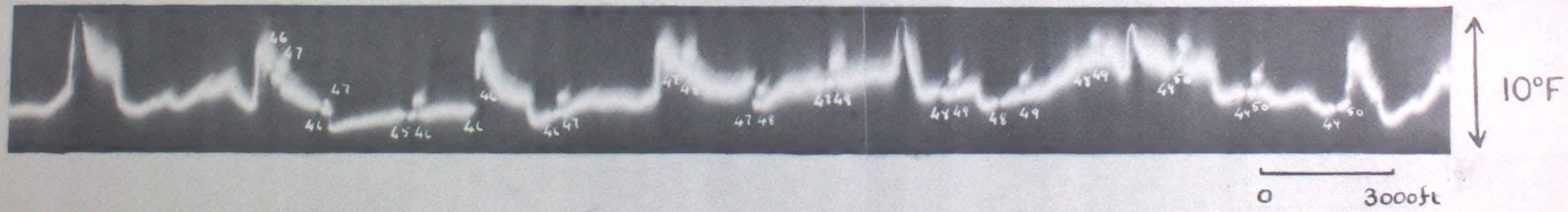
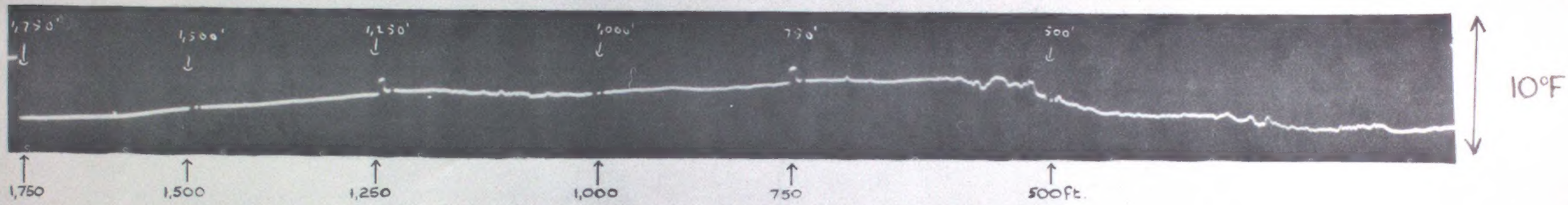


Fig. 16

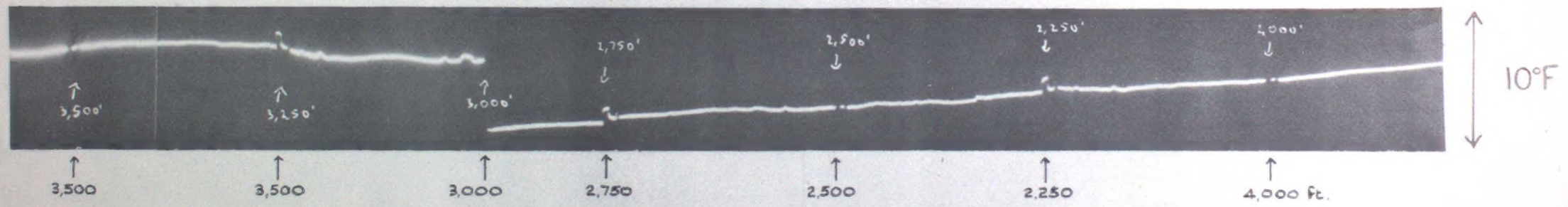
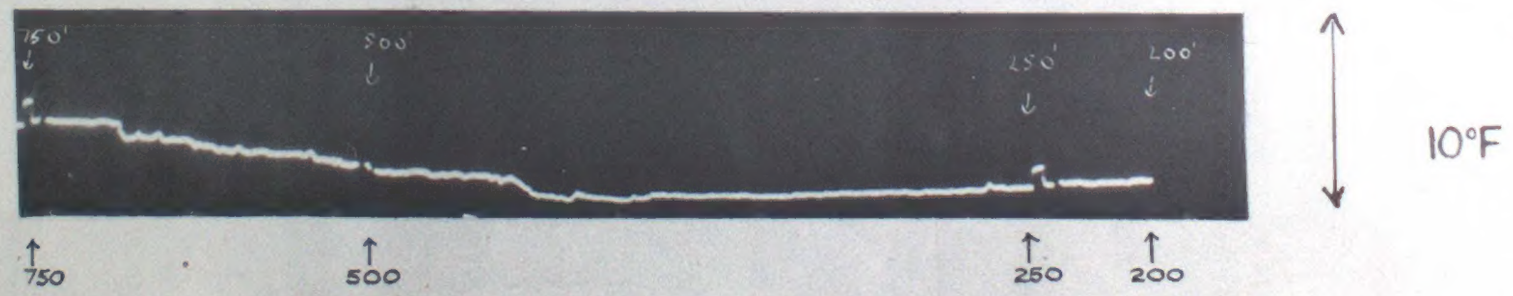
SLOW DESCENTS OVER SEA USING THE ULTRA RAPID THERMOMETER

M.R.P. 875

FLIGHT 20 1750 FEET TO 250 FEET, SHEWING INVERSION BELOW 600 FEET



FLIGHT 20 3600 FEET TO 1750 FEET



FLIGHT 20 750 FEET TO 200 FEET, SHEWING INVERSION TWENTY MINUTES LATER